LITERATURE
on
DESIGN TECHNIQUES
and
ANALYTICAL METHODS
for
BRITTLE MATERIALS

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ARMOUR RESEARCH FOUNDATION OF ILLINOIS INSTITUTE OF TECHNOLOGY

LITERATURE ON DESIGN TECHNIQUES AND ANALYTICAL METHODS FOR BRITTLE MATERIALS

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PREFACE

The second task of the first phase of Armour Research Foundation program 8259, UTILIZATION OF REFRACTORY NON-METALLIC MATERIALS IN FUTURE AEROSPACE VEHICLES, was a "Literature Review of Design Techniques and Analytical Methods". The first part of this task, a comprehensive literature search, is presented here as Volume I of the Final Report on Phase 1 - Task 2; "Literature on Design Techniques and Analytical Methods for Brittle Materials". Volume II, "Review of Structural Design Techniques for Brittle Components under Static Loads" will also be issued this month.

The program is being conducted for the Aeronautical Systems Division, Air Force Systems Command, the United States Air Force under Contract AF33(657)-8339. The report period is February 1963 to May 1963. Mr. R. L. McGuire of the Flight Dynamics Laboratory is Technical Monitor for ASD.

This literature search was compiled by R. L. Barnett (Task Leader), P. C. Hermann, A. Humphreys, and M. D. Tamulionis. Dr. N. A. Weil, Director of Mechanics Research, is over-all program manager.

Respectfully submitted,
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LITERATURE ON DESIGN TECHNIQUES AND ANALYTICAL METHODS FOR BRITTLE MATERIALS

This report presents the results of a literature search which had as its objective the collection of pertinent information on analytical methods, existing design criteria, and currently practiced construction concepts for materials that behave in a brittle manner. The search was divided into the ten areas listed in the table of contents. Using standard survey techniques, the most recent and important literature in each catagory was identified and procured, and with two exceptions, this stage constituted the complete search. In the two areas, Statistical Static Strength Theories and Fatigue, a more elaborate survey was conducted. Here, the bibliographies of each document collected were studied and every unordered reference on the subject was ordered. This convergent process was continued until almost no new references could be found.

Because all the documents surveyed were actually obtained, it was possible to summarize each item by using the author's synopsis, abstract, summary, or conclusion. The various entries in each subject area are listed alphabetically with the exception, once again, of the catagories on Statistical Theories and Fatigue. The survey was sufficiently complete in these areas to rate these documents according to a "popularity index".

The popularity index is a ratio between the number of references made to a paper and the total number of documents on the subject since the paper was published. Since papers published in 1961 and 1962 were not readily available for reference by contemporary papers, any attempt to determine their reference ratio would be unrealistic. Therefore, all papers collected which were published in these years were simply listed alphabetically at the beginning of the catagory. The popularity index of a paper was computed in the following manner. All the cards for a given category were collected and the number of papers published each year and the cumulative numbers of papers were recorded. Then the number of times a given paper was referred to by other papers in the same category was noted. This number divided by the cumulative number of papers published for the

year of the given paper's publication gave the popularity index for the paper. For example, the paper "Life Testing", by B. Epstein and M. Sobel, published in 1953, was referred to seven times by the fifty-four papers written between 1953 and 1962 which appeared in our category of "Fatigue". The popularity index is then 7/54 or 13 percent.

STATISTICAL STATIC

STRENGTH THEORIES

ARMOUR RESEARCH FOUNDATION OF ILLINOIS INSTITUTE OF TECHNOLOGY

Anthony, Frank M., and Mistretta, Andrew L., Leading-Edge Design with Brittle Materials. (Aerospace Engineering, pp. 20-52, November, 1961). 1

Abstract

The leading edge of a hypersonic glider is subjected to extreme operating environments. Design of such a structural component requires the consideration of many variables of flight performance requirements, vehicle geometry, material characteristics, and component geometry. The major design problem is to provide a leading edge which will resist the thermal and aerodynamic loadings imposed and will not oxidize despite high operating temperatures.

This paper will discuss the graphite leading edge as a structural component designed for specific application, and the philosophy and methods of analysis used to ensure structural usefulness despite the brittleness of the construction material. The approach should be useful for other materials and other design problems.

Bakeman, D.C., Missle Design for the Effects of Winds Aloft. (Aerospace Corporation, El Segundo, California, DCAS-TDR-62-190; Report No. TDR-69(2116)TN-1; Contract No. AF 04(695)-69; prepared for Air Force Systems Command, United States Air Force, September 13, 1962). 2

Abstract

A major problem in the design of large booster missiles is the proper consideration of the effects from winds aloft. Since wind magnitude and direction are statistical in nature, the problem can only be solved by the use of statistical techniques.

This report suggests that the design requirement be a given probability of failure or launch delay due to winds aloft, or an optimization between cost (in terms of weight, schedules, etc.) and the probability of failure or launch delay. A methodology is then presented, along with pertinent background information and discussion, for designing to any of those requirements. Also presented is a procedure for a prelaunch wind check in which wind effects magnitudes are predicted for a flight.

Gilvarry, J.J., Fracture of Brittle Solids. I. Distribution Function for Fragment Size in Single Fracture (Theoretical). (Journal of Applied Physics, 32, 3, March, 1961). 3

Abstract

For single fracture of a brittle solid, the distribution function for fragment size is obtained on the basis of Griffith's theory of brittle strength (which postulates crack propagation when pre-existent flaws are activated by stress). Three assumptions are made: (a) Fracture proceeds by activation of flaws in the volume of the specimen, in fracture surfaces through the specimen, and in the edges produced by fracture surfaces, (b) the corresponding volume, facial, and edge flaws are distributed independently of each other when activated, and (c) activated flaws of a particular type are distributed at random, individually and collectively, in the sense of Fry. These assumptions yield directly and uniquely the probability dp(l, s, v) of formation of a fragment with total edge length, total face area, and total volume in the ranges l to l + dl, s to s + ds, and v to v + dv, respectively, as $e^{-Q}dQ$ in the general case, with Q linear in l, s, and v. The derivation yielding this Poisson form requires no assumption on the shape of a fragment or the type of fracture surface. The number dn(l, s, v) of fragments with total edge length, total face area, and total volume in the ranges l to l + dl, s to s + ds, and v to v + dv, respectively, is evaluated as the product of dp(l, s, v) by the a priori number q of particles with these values of l, s, and v. The distribution function dn(l, s, v) meets the necessary physical requirement that the fracture process conserve volume independently of particle shape. By assuming that all fragments are geometrically similar, one can replace dp(l, s, v) and dn(l, s, v) by forms p(x)dx and n(x)ds, respectively, which depend only on a mean linear dimension x of a fragment. The resulting expression for y, the cumulative fraction of the initial volume corresponding to fragments of dimension up to x, then yields rigorously forms of the empirical equations of Schuhmann and of Rosin and Rammler for this quantity, as limiting cases for x small. The conclusion follows that activation of edge flaws represents the dominant mode of fragmentation in general. The moments of the distribution corresponding to the total number, the total edge length, and the total surface of the fragments are divergent; this anomaly is explained as the result of neglect of flaw depletion.

Goode, Henry P., and Kao, John H.K., Sampling Plans Based on the Weibull Distribution. (Proceedings of the Seventh National Symposium on Reliability and Quality Control, pp. 24-40, 1961). 4

Abstract

This paper presents a proposed set of acceptance-sampling plans for life testing and reliability when the underlying life distribution is of the Weibull form. Inspection of the sample is by attributes with the life test truncated at a preassigned time, t. A set of conversion tables is also provided from which attribute sampling-inspection plans of any desired form may be designed for the Weibull model or from which the operating charac-

teristics of any given plan may be determined. A procedure using these tables for applying the MIL-STD-105B plans to reliability and life-testing applications is included.

Haight, Frank A., Index to the Distributions of Mathematical Statistics. (Journal of Research of the National Bureau of Standards - B. Mathematics and Mathematical Physics, 65B, 1, January-March, 1961). 5

Abstract

A fairly complete index of references to results on statistical distributions published before January, 1958, is presented. The material given for each distribution is a list of references relating to: (a) functions and constants which characterize the distribution, (b) derived distributions, (c) estimation, (d) testing statistical hypotheses, (e) miscellaneous. The distributions covered are characterized as normal, type III, binomial, discrete, distributions over (a, b), distributions over (a, ∞), distributions over $(-\infty, \infty)$, miscellaneous univariate, miscellaneous bivariate, and miscellaneous multivariate. The number of entries varies from one or two for less well-known distributions to several hundred for the normal distribution. This index should serve to eliminate unnecessary derivation of results already in the literature.

Hawley, G. O., and Ostle, B., Training for Reliability and Quality Control. (Proceedings of Seventh National Symposium on Reliability and Quality Control, pp. 1-6, 1961). 6

Abstract

Whenever specialized areas of professionalism gain recognition within a broader framework of activity, the subject of training, or education, for this area of specialization inevitably arises. This has occurred for Quality Control in the years since 1940 and for Reliability in the years since 1955. It is our belief that the subject of training in each of these disciplines has much in common and that a discussion of needs, the steps taken to satisfy these needs, and the steps yet to be undertaken, is warranted at this time.

The training needs for Reliability and Quality Control are discussed in the light of today's requirements. The subject is developed by comparing what industry seeks in an ideal reliability and quality control engineer with what is found when interviewing recent college graduates.

The steps taken by industry to close the gap disclosed by the preceding comparison are summarized, with special attention being given to Sandia Corporation experience. Recommendations of both a general and specific nature are made.

Kao, John H., The Beta Distribution in Reliability and Quality Control. (Proceedings of the Seventh National Symposium on Reliability and Quality Control, pp. 496-511, 1961). 7

Abstract

A statistical distribution known as the Beta distribution or Pearson Type I distribution is of such considerably statistical importance that its originator Karl Pearson (23) and his associates labored over a period of eight years to compute a comprehensive table for it. Many of the commonly used distributions are related to the beta distribution either arising as a special case of it or through simple transformations or as results of some limiting processes. The beta distribution has two shape parameters and covers the range of zero to unity. However, it is easy to introduce location and scale parameters so that it will cover any arbitrary finite range on the real line. This distribution appears to have been very much neglected by the quality control and reliability engineers. The present paper will concern itself with some applications of the beta distribution to a few important statistical problems in the area of quality control and reliability engineering. Much of the material covered in this paper is scattered in the published literature, some of the results given here appear for the first time. In an effort to unify these, the paper will start with an outline on the properites of the beta distribution, its relationship with other more well-known statistical distributions, and then follow with the applications. The applications will include designing single sampling plans by attributes for infinitely many choices of consumer's and producer's risks, solving tolerance limit problems for a continuous array of population coverages and confidence coefficients, and finding confidence bands on lifelength distributions for which the data are usually truncated and self-ranked. These applications will be made graphically on the beta probability chart of Hartley and Fitch and will be illustrated by numerical examples in each case. Hypothesis testing and confidence limits concerning the means or failure rates of the Weibull distribution based on failure data truncated either by item or by time will also be included.

Lester, Jr., Joseph T., Statistical Planning to Reduce Number of Tests. (ASME Paper No. 62-MD-30, 1962). 8

Abstract

Mathematical, statistical, and computational techniques have been applied profitably to a wide variety of machine-design problems to reduce the amount of trial-and-error experimentation required and to aid in selection of optimum designs. Examples are presented which illustrate the use designed experiments and efficient methods for exploring response surfaces.

Lieberman, Gerald, J., and Miller, Jr., Rupert G., Simultaneous Tolerance Intervals in Regression. (Technical Report No.59, Contract Nonr-225(53) - NR-042-002, with the Office of Naval Research, April 30, 1962). 9

Abstract

Joint prediction intervals (based upon the original fitted model) for K future responses at each of K separate settings of the independent variable have been treated by Lieberman. When K is unknown and possibly arbitrarily large, these results do not apply. A solution to the problem of arbitrary K is given in terms of tolerance intervals on the distributions of future observations, the intervals being (probabilistically) simultaneous in each possible value of the independent variable. Four alternative techniques are proposed and compared for their applicability in different situations. The first is the simultaneous extension of the Wallis technique. The other three are based on Scheffe simultaneous confidence principles. One gives intervals for a fixed central proportion P of the distribution which are simultaneous in all values of the independent variable; the other two give intervals simultaneous in the independent variable and different central proportions P. A numerical example is analyzed, and some remarks are made on the applicability of the Scheffe techniques to the detection of outliers.

Ogden, H.R., and Beatty, G.H., Statistical Analysis of Tensile Properties of Heat-Treated Mo-O.5Ti Sheet. (DMIC Memorandum 101, April 24, 1961, Defense Metals Information Center, Battelle Memorial Institute, Columbus, Ohio). 10

Abstract

The Defense Metals Information Center has conducted statistical analyses of tensile properties of the Mo-0.5Ti alloy. Statistical tests of significance based on these findings indicate the following conclusions.

Direction of testing affects all five tensile properties; ultimate and yield strength are higher in the transverse direction, while elongation is higher in the longitudinal direction. Gage has little effect on ultimate or yield strength but has a pronounced effect on elongation (an increase in gage causes an increase in elongation). Direction of testing does not interact with gage effect; that is, the effect of gage on all five tensile properties is about the same in both the longitudinal and transverse directions.

Pinkham, Roger S., An Approximation to the Probability Integral of the Gamma Distribution. (The Statistics Center, Rutgers-The State University, New Brunswick, New Jersey. Technical Report No. 8, for Office of Naval Research under Contract Nonr 404(16), September, 1961). 11

Schwartz, M.D., Confidence Intervals using Parametric Estimators and Nonparametric Methods. (Aerospace Corporation, As 1951.2-212, August, 1962). 12

Schwartz, M. D., Evaluation of the Normal Distribution with Many Variables for the Case of Low Probability of Failure. (Aerospace Corporation, 1951.2-217, August, 1962). 13

Schwartz, M.D., A Method for Computing the Probability of Failure Due to Winds for a Class of Missles. (Aerospace Corporation, 1951.2-211, August, 1962). 14

Siddiqui, M.M., Some Problems Connected with Rayleigh Distributions. (Journal of Research of the National Bureau of Standards -D. Radio Propagation, Vol. 66D, No. 2, March-April, 1962). 15

Abstract

This is an expository paper presenting the following: (1) the origin, and (2) the properties of the Rayleigh distribution; (3) the most efficient

estimators of its parameters; (4) a test of the hypothesis that a set of observations is from a Rayleigh distribution; (5) the distribution of the ratio of two independent Rayleigh variates; and (6) the Rayleigh process derived from a normal process.

Wallhaus, Robert Arthur, A Statistical Study of Factors Influencing the Strength of Glass Fibers. (Technical Memo No. 187, T and AM Report No. 217, Sponsored by U.S. Naval Research Laboratory, Contract No. Nonr 2947 (02)(x), NRL Project 62 R05 19A, Department of Theoretical and Applied Mechanics, University of Illinois, Urbana, Illinois, May, 1962). 16

Abstract

A statistical concept is investigated for the purpose of describing the breaking strengths of glass fibers. The parameters of the Weibull distribution function are calculated and used to study the effects of time, static load, humidity, annealing, and various degrees of mechanical damage on the fracture strength of glass fibers and fiber bundles.

The breaking strength of a bundle of glass fibers is analyzed by use of the proposed statistical distribution, and the results predicted by this analysis are compared with experimentally determined values of ultimate bundle strength.

Weil, N.A., Bortz, S.A., and Firestone, R.F., Factors Affecting the Statistical Strength of Alumina. (Research Conference on Structure and Properties of Engineering Materials, March 12-13, 1962). 17

Abstract

This program was undertaken to determine the applicability of statistical fracture theories to inorganic ceramics, and to define the major parameters affecting fracture strength. Specimen shapes were developed, adaptable to a broad range of loading conditions and volumetric variations.

The effect of five variables was investigated on the strength of Wesgo AL995: prior thermal history, specimen finish, test temperatures, environment, and specimen size. Of these parameters, specimen size, testing temperature, surface treatment, and thermal history were found to have a primary influence on fracture strength. Environmental effects

(moisture content) were found to be significant only for ground specimens tested at 20° C.; at 1000° C. all environmental influences became negligible.

Fracture in Wesgo AL995 at room temperature is governed purely by surface induced failure mechanisms. Both Weibull constants, the "flaw density parameter", m, and the "zero strength", σ_u, are highly sensitive to surface treatment and thermal history. Specifically, grinding increases the value of m but leaves σ_u unaltered; annealing increases m while also dropping the value of σ_u to zero. Both conditions act to weaken the material. This weakening effect is particularly pronounced in the case of annealed specimens; this is thought to be ascribable to the destruction of a beneficial residual stress distribution originally existing in the material due to the subsequent annealing treatment.

Wilk, M. B., Ananadesiken, R., and Huyett, M. J., Probability Plots for the Gamma Distribution - Case 20878-5. (Bell Telephone Laboratories, MM-61-121-16, March 16, 1961). 1.

Abstract

The use of "probability plots" for evaluation (informal) of distributional assumptions in the light of the sample, for semigraphical estimation of parameters, for assistance in analyzing experimental data and for other purposes is an old and reasonably honorable statistical procedure which has been discussed by a number of writers.

The basic idea is that a random sample from a population will tend to be representative in the sense that the empirical cumulative distribution will approximate the theoretical function. Hence, if the sample is large enough, the sample order statistics when plotted against the "corresponding" quantiles of the theoretical distribution will tend to yield a set of approximately collinear points, clustering about a line of slope 1 passing through the origin.

Popularity Index - 25.5%

Weibull, W., A Statistical Theory of the Strength of Materials. (Ingeniorsvetenskapsakademiens, Handlingar, 151, 15, Stockholm, 1939). 19

Abstract

Part I. The classical theory of strength is obviously incompatible with numerous results of experimental research. This discrepancy may be bridged over by considering as an essential element of the problem the

dispersion obtained in experimental measuring of the ultimate strength. Viewed from this standpoint, the ultimate strength of a material can not be expressed by a single numerical value, as has been done heretofore, and a statistical distribution function will be required for this purpose. The application of the calculus of probability leads to the fundamental law of the theory, viz., that the probability of rupture (s) at any given distribution of stresses (σ) over a volume (V) is determined by the equation.

$$\log (1 - S) = - \int_{V} n(\sigma)\, dv$$

where $n(\sigma)$ is a function characteristic of each particular material. This fundamental formula allows to compute the influence of the volume on the ultimate strength, the relation between tensile, bending, and torsional strength, etc.

An experimental substantiation of the theory is provided by observations obtained from tensile, bending, and torsional tests on rods made of stearic acid and plaster-of-Paris.

Part II. In this part of the paper a description is given of the graphic method used for the statistical treatment of the observations and of some measuring series relating to strength of materials under the action of mechanical and electrical forces. It is shown that the material function may be expressed by the formula

$$n(\sigma) = \left(\frac{\sigma - \sigma_u}{\sigma_o} \right)^m$$

where σ_u, σ_o, and m are constants characteristic of the material. This formula applies to statistically homogenous materials.

Popularity Index - 14.1%

Weibull, Waloddi, A Statistical Distribution Function of Wide Applicability. (Journal of Applied Mechanics, 18, pp. 293-297, September, 1951). 20

Abstract

This paper discusses the applicability of statistics to a wide field of problems. Examples of simple and complex distributions are given.

Popularity Index - 13.4%

Epstein, Benjamin, Statistical Aspects of Fracture Problems. 21
(Journal of Applied Physics, 19, pp. 140-147, 1948).

Abstract

In recent years there has been an increasing interest in the development of statistical theories of strength. A main aim of these theories is to explain in a reasonable way such things as the dependence of the strength of specimens on their volume or length. In this paper it is pointed out that the problems posed by these models are equivalent to an important problem in mathematical statistics, namely, the distribution of the smallest value in samples of size n drawn from a population having some probability density function f(x). The calculations made by mathematical statisticians give a far more complete description of the results to be expected than do the estimates to be found up to now in the technical literature.

Popularity Index - 13.3%

Weibull, W., The Phenomenon of Rupture in Solids. (Ingenior- 22
svetenskapsakademiens, Handlingar NR 153, 1939).

Abstract

Experimental investigations intended to serve as verifications of a statistical theory of strength of materials have shown that the rupture in solids may follow two fundamentally divergent courses resulting in different mathematical expressions for the probability of rupture. Formulae for these two possibilities are deduced for isotropic and anisotropic materials.

With a view to facilitating the numerical computation of the distribution constants by arithmetical methods, formulae are deduced and values tabulated.

The theoretical investigations deal also with series comprising two or more components.

As experimental evidence for the theory, two test series are shown, which illustrate the two above-mentioned possibilities.

Popularity Index - 12.1%

Gumbel, Emil J., Statistical Theory of Extreme Values and Some Practical Applications. (National Bureau of Standards, Applied Mathematics Series - 33, February 12, 1954). 23

Abstract

This monograph is based on four lectures given at the National Bureau of Standards under the sponsorship of the Applied Mathematics Division. The aim of this publication is to make the statistical theory and techniques of extreme values readily available to scientists and engineers. This seems necessary because the original papers, partly written in foreign languages and published in remote journals, are not easy to find.

The present study started as a compilation from papers and brochures that I had written during the last twenty years. However, it soon became evident that such a composition, even with the necessary condensation, was impossible, and that it was more adequate to start afresh with a new and independent approach.

The first lecture outlines some of the practical problems to which the theory pertains. The second lecture introduces certain new statistical tools necessary for the theory, which is developed in the third lecture, first in exact, then in asymptotic form. The fourth lecture shows a series of practical applications and gives all numerical details for enabling interested readers to apply the method to their own problems.

Popularity Index - 10.5%

Tippett, L.H.C., On the Extreme Individuals and the Range of Samples Taken from a Normal Population. (Biometrika, 17, p. 364, 1925). 24

Abstract

The problem of the range of samples arises as a special case of Galton's Difference Problem, first given by Professor K. Pearson in 1902 (1). Together with the allied problem of the extreme individuals, it has engaged the attention of other writers (2) (3) (4), but a complete solution has not yet been given. This would involve the determination of the distribution of the range and of the extremes for a large number of samples. Attempts are here made in some measure to supply this deficiency.

Popularity Index - 9.8%

Freudenthal, A.M., Safety and the Probability of Structural Failure. (Transactions American Society of Civil Engineers, 121, p. 1337, 1956). 25

Abstract

The preoccupation, in recent years, on the part of structural engineers with problems of the carrying capacity and of the safety of structures is the sign of a growing realization that significant advances in the theory of structures can be expected from a critical re-evaluation of the basis and the premises of such theory rather than from further refinement of the methods of stress-analysis. Present methods of structural analysis produce designs the safety of which is neither balanced nor clearly specified; the formulation of a rational concept of safety and of methods for the evaluation of a measure of safety represent tasks of considerable urgency in structural research. The fact that current design procedures in the majority of cases result, fortunately, in structures of excessive though unbalanced safety rather than in unsafe structures is an indication of the caution exercised by designers and the authorities responsible for design specifications rather than of the reliability and accuracy of design procedures.

From the realization that the design, at present, of a structure for future use must necessarily embody predictions of expected performance of the structural material based on past experience (materials tests), as well as predictions of expected load-patterns and intensities extrapolated from past observations (load records), it follows that, since such predictions by their very nature cannot be made with certainty but only with a certain measure of probability, the concept of probability must form an integral part of any rational design: any conceivable condition of the designed structure is necessarily associated with a numerical measure of the probability of its occurrence. It is by this measure alone that the reality and structural significance of a specified condition can be evaluated.

This does not imply that the use of probability theory is in itself sufficient to make design procedures more adequate and reliable; probability concepts and statistical methods based thereupon, while extremely valuable tools in design, can be effectively used only in conjunction with a thorough knowledge of the operating conditions of the structure and of its structural action, and with sound engineering judgment. They will provide objective guidance for such judgment whenever random phenomena and random magnitudes have to be considered; they are useless in the analysis of phenomena and effects the variation of which is not random.

Popularity Index - 9.7%

Fisher, R.A., and Tippett, L.H.C., Limiting Forms of the Frequency Distribution of the Largest or Smallest Member of a Sample. (Proceedings Cambridge Philosophical Society, 24, p.180, 1928). 26

Abstract

In a previous paper on the subject of the distribution of the largest member of a sample from a normal population, one of the authors has given constants involving the first four moments for samples up to 1000. In this paper, possible limiting forms of such distributions in general are discussed. It will appear that a particular group of distributions provides the limiting distributions in all cases, and that the case derived from the normal curve is peculiar for the extreme slowness with which the limiting form is approached.

Popularity Index - 9.7%

Gumbel, E.J., Probability Tables for the Analysis of Extreme-Value Data. (National Bureau of Standards, Applied Mathematics Series - 22, July 6, 1953). 27

Popularity Index - 9.5%

Davidenkov, N., Shevandin, E., and Wittmann, F., The Influence of Size on the Brittle Strength of Steel. (Journal of Applied Mechanics, 14, p 62, 1947). 28

Abstract

In this paper the influence of size effect on the impact cold brittleness of carbon steel is discussed. Static bending of notched specimens shows the same size effect, so that an assumption of the special role played by high velocity must be rejected. The experiments on the determination of the critical temperature of brittleness for impact-tension tests also display the size effect and therefore exclude any possible influence of the stress gradient. Experiments on static tension and bending of cylindrical specimens of brittle phosphorous steel in liquid air reveal the statistical nature of the size effect and give a good qualitative verification of Weibull's theory. Weibull's homogeneity exponent m calculated from experiments with tension and bending is found to have nearly identical values (namely 23.5 and 25.4). The theoretical values of the brittle strength of small specimens calculated with this value of m differ from the experimental

ones by about 3 percent; the ratio of the strengths in the case of bending and tension is found experimentally to be 1.40 against 1.39, according to the theory. The "scatter" in particular values for large specimens, as predicted by theory, is smaller than for small ones.

Popularity Index 7.7%

Peirce, Fredrick Thomas, Tensile Tests for Cotton Yarns, v. - The Weakest Link - Theorems on the Strength of Long and of Composite Specimens. (Journal Textile Institute, Trans. 17, 355, pp. T355-T368, 1926).

Abstract

It is a truism, of which the mathematical implications are of no little interest, that the strength of a chain is that of its weakest link. It is equally true that the strength of a test specimen is that of its weakest element of length, whether it be a metal rod, a thread of yarn, or a cotton hair. This fact distinguishes the quantity, breaking load, from most other quantities, such as weight of which the value is determined by the average over-all elements of the length. Tensile strength thus decreases with the length of specimen in a way which is definitely calculated from the distribution of strength of short specimens. The decrease in mean strength and in irregularity is directly proportional to the irregularity of the short specimens and to a factor, depending only on the multiple by which the length is increased and very simply calculated therefrom.

Variability along a specimen is shown necessarily to introduce negative skewness into all frequency curves of strength, counteracting or reinforcing any skewness that may arise from methods of production, and this must be taken into consideration when drawing conclusions from the shape of strength frequency curves. In cotton yarns, the method of production tends to produce positive skewness which is found with specimens of 3 inches. This is obliterated to yield a symmetrical curve by increasing the length to a foot or so, while leas show decided negative skewness. More generally, skewness is produced by irregularity in the frequency curves of any quantity, "when the deviations of individual values are affected unequally by equal deviations of opposite sign among the constituent elements of a specimen," a criterion which fits most elastic measurements.

The relations between the strength of fibres, yarns, leas, and fabrics have often been studied empirically, but they are subject to so many disturbing factors that measurements do not lead to definite or simple conclusions, in the absence of a logical basis for comparing the results. In the present paper, five cases of specimens composed of parallel elements are analyzed for a relation between the strength of the whole and of the parts. Actual specimens of all kinds of materials may reproduce the conditions more or less closely. The lea test can be brought under a simple case if modified as suggested in Paper I of this series.

A correction is given for measurements of tendering when only a fraction of the length of a specimen is subjected to treatment, such as wear or exposure to light.

The present paper is mathematical throughout, but the conclusions are condensed into simple forms applicable to experimental results in this series or elsewhere.

Popularity Index - 6.4%

Lieblein, Julius, On the Exact Evaluation of the Variances and Covariances of Order Statistics in Samples from the Extreme-Value Distribution. (Annals of Mathematical Statistics, 24 (2), pp. 282-287, 1953). 30

Abstract

This paper develops explicit closed formulas for the covariances of order statistics in samples from the extreme-value distribution which involve only tabulated functions. Such results do not appear to have been given previously. They have been used in an investigation of the estimation of extreme-value parameters by means of order statistics which will be presented in a fuller report to be submitted to the National Advisory Committee for Aeronautics.

Popularity Index - 6.3%

Institution of Structural Engineers, Report of Structural Safety. (Structural Engineering, 33, p. 141, 1955). 31

Abstract

The committee was appointed in December, 1951, with the following terms of reference:

(a) To review structural safety problems, including modes of specifying margins of safety for design purposes.

(b) To prepare a report for discussion and for publication.

The committee has met 20 times between then and October, 1954, and this report sets out its conclusions in a form thought suitable for written discussion.

The report seeks to advance current ideas regarding structural safety and to provide a basis for the more rational formulation of safety clauses in future revised or new codes of practice.

The committee has not attempted to compile a comprehensive bibliography on structural safety problems, but in Appendix V gives some valuable general references wherein may be found useful lists of relevant papers.

Popularity Index 6.2%

Salmassy, Omar K., Bodine, Edward G., Duckworth, Winston H., and Manning, George K., Behavior of Brittle-State Materials. Part II. (Battelle Memorial Institute, WADC Technical Report 53-50, June, 1955). 32

Abstract

A critical survey was made of the significant theories of strength, for guidance in developing relationships among the strength properties of ceramics. The mechanistic theories appeared to offer the greater possibilities, but no theory treated all controlling variables, and all theories lacked adequate experimental support. The need remains apparent for a unified theory and supporting experimental data.

The principal laboratory effort was on the size dependence of strength. Both plaster and a nickel-titanium carbide body decreased in apparent strength with increases in gage-section size in bend tests. In an extensive program of bend tests on plaster to record details, strength decreased with increases in either gage-section length or gage-section breadth in about the same manner. However, the apparent strength increased with increases in gage- section depth. The possibility of the true size effect's being masked by size-dependent testing variables was indicated. There was no trend apparent in the standard deviation of strength values with variations of gage-section length, breadth, or depth.

Further information was obtained on the effect of the type of test on mechanical properties. Of particular interest is the fact that, with sufficient refinement, the bend and torsion tests appear to yield practically the same strength values. The development and refinement of tests was continued in an effort to obtain the precise mechanical-property data needed in this program.

Popularity Index - 5.9%

Weibull, Waloddi, A Survey of "Statistical Effects" in the Field of Material Failure. (Applied Mechanics Reviews, 5, 11, p. 449, November, 1952). 33

Popularity Index - 5.8%

Volkov, S.D., Statistical Strength Theory, (Gosudarstvennoye Nauchno - Teckhnicheskoye Izdatel'stvo, Mashinostroitel'noy Literatury, Moskva, 1960, Sverdlovsk). 34

Abstract

The statistical strength theory combines new methods for the computation of machine parts and equipment components with a consideration of phenomena that are significantly affected by the structural inhomogeneousness of technological materials (the process of fracture, scale effect, etc.). A characteristic feature of the new methods is the application of mathematical statistics and probability concepts. This book proposes to develop the new strength theory and its practical application in the mechanical engineering field. It is dedicated to mechanical engineers, metallographers, and designers concerned with general questions of strength as well as with practical computations and experimental investigations of the strength of materials and machine and structural parts.

Popularity Index - 5.6%

Pugsley, Professor Alfred Grenvile, Concepts of Safety in Structural Engineering. (Journal of Institution of Civil Engineering, 36, p. 5, March, 1951). 35

Abstract

Some introductory paragraphs outline the early development of margins of safety around problems of construction in masonry, cast iron, and wrought iron; and the gradual emergency of factors of safety. The safety problems arising later with mild steel and reinforced concrete, and with airships and aeroplanes, are then discussed; and the development of load factors and the increasing interest in proof loads are outlined. It is then shown how the assessment of safety by reference to accident statistics led, in military aviation, to a broader concept of safety based on accident risk; how this approach has since been applied to other matters such as the consideration of floor loads and wind loads for buildings; and how it can embrace such troubles as failure by fatigue or by flutter. The safety problems arising from the structural use of castings, and of other materials of low ductility, are discussed, as well as the exploitation of ductility in the plastic design method for mild-steel building frames.

A final section is devoted to a review of present concepts and measures of safety and to the consideration of some possible future trends. The increasing use of load factors and the need for more control of ductility

and of deflexions generally, and for the specification of design life, are noted. A possible trend towards three wider philosophies is put forward, each associated respectively with the minimization of risk to human life, with the desire for economic efficiency, and with the desire for military effectiveness. The importance to any concept of safety of the further study of external loads and of more experimental work on structures is emphasized. In conclusion, reference is made to the need for avoiding too rigid or detailed a control over design, even from the safety standpoint; as in other branches of engineering, freedom is essential for development.

Popularity Index - 5.2%

Chernoff, Herman, and Lieberman, Gerald J., Use of Normal Probability Paper. (Journal of the American Statistical Association, 49, pp. 778-735, 1954). 36

Abstract

Normal probability paper is so designed that the cumulative distribution function of a normally distributed chance variable appears as a straight line. It is a common practice to plot the observations of a sample on this paper to obtain a graphical check for normality or to obtain a graphical estimate of the mean and variance of the population. Textbooks, however, are not very specific about methods for plotting, for, although the ordered observations are plotted along the abscissa, some uncertainties about the corresponding ordinates are left unresolved. The purpose of this paper is to indicate, with a special example, that any graphical technique should depend to a large extent on the purpose for which the graph is drawn. In particular, it presents tables covering sample sizes up to 10 for selecting the ordinates on normal probability paper so as to obtain "optimum" graphical estimates of the mean ξ and the standard deviation σ of a normal distribution. The somewhat more complicated problem of selecting the ordinates to obtain an "optimum" test for normality is not discussed.

Popularity Index - 5.2%

Lieblein, Julius, A New Method of Analyzing Extreme-Value Data. (National Advisory Committee for Aeronautics, Technical Note 3053, January, 1954). 37

A new method is presented and proposed for analyzing extreme-value data which may arise in a wide variety of applications.

Classical applications of statistical methods, which usually concern average values, are inadequate when the quantity of interest is the largest (or smallest) in a set of magnitudes. This is the situation in a number of fields, for example, gust loads of an airplane in flight, the highest temperatures or lowest pressures in meteorology, floods and droughts in hydrology, breaking strengths in materials testing, breakdown voltage of capacitors, and human life spans, in all of which applications of methods for dealing with extremes have already been made.

Discussion of the proposed method is preceded by the necessary statistical theory which also furnishes a basis for evaluating the new method in relation to existing ones. The techniques described provide a simple means for estimating the necessary parameters, making predictions from the fitted curve, estimating the reliability, and evaluating the efficiency of the method in relation to other methods. Moreover, these quantities are all produced by a single set of computations involving just two work sheets. This background material is not essential to an application of the method and may be omitted if desired. The method itself is summarized for practical convenience, illustrated step by step, and compared with present procedures. The advantages of the proposed method are also discussed, chief among which are: (1) For the first time there is available an unbiased estimator of known efficiency. (2) The proposed estimator appears to be more efficient than a simplified form of the Gumbel estimator in many practical cases, namely, for samples of about 20 or more and a probability level $P = 0.95$ or more. The improvement in efficiency increases with increasing P or increasing sample size. When compared with the original Gumbel estimator, the proposed one is up to twice as efficient. (3) The confidence intervals are found to a closer approximation and are in many cases narrower than the ones in the Gumbel method.

Thus, while the Gumbel techniques are very useful in many cases, the methods developed in this report will be of special interest to those who must extract the greatest amount of information from a limited set of costly data.

Popularity Index - 4.9%

Chernoff, Herman, and Lieberman, Gerald J., The Use of Generalized Probability Paper for Continuous Distributions. (Annals of Mathematical Statistics, 27, pp. 806-18, 1956). 38

Abstract

The problem of plotting on probability paper is extended to continuous distributions which are completely specified except for scale and

location parameters. Necessary and sufficient conditions are given to ensure that the plot which is optimal for estimating the scale parameter is also optimal for estimating each of the percentiles.

Popularity Index - 4.9%

Epstein, Benjamin, Application of the Theory of Extreme Values in Fracture Problems. (Journal of the American Statistical Association, 43, pp. 403-412, September, 1948). 39

Abstract

In this paper it is shown that the theory of extreme value is pertinent to the treatment of certain aspects of the fracture or breakdown of materials used in modern technology. An attempt is made to integrate some of the results scattered through the technical literature.

Popularity Index - 4.9%

Epstein, Benjamin, and Brooks, Hamilton, The Theory of Extreme Values and Its Implications in the Study of the Dielectric Strength of Paper Capacitors. (Journal of Applied Physics, 19, pp. 544-550, 1948). 40

Abstract

In this paper it is shown that the statistical theory of the distribution of extreme values is pertinent to the study of the way in which the breakdown strengths of paper capacitors depend on capacitor size. The theory presented in this paper permits a quantitative explanation of this phenomenon and results are given which should be useful to design engineers.

Popularity Index - 4.8%

Freudenthal, Alfred M., The Safety of Structures. (Transactions American Society of Civil Engineering, 112, p. 125, 1947). 41

Abstract

The purpose of this paper is to analyze the safety factor in engineering structures in order to establish a rational method of evaluating

its magnitude. The discrepancy between the highly refined procedure of modern design and the rather arbitrary manner of choosing the safety factor is seriously hampering the development of more effective design methods based upon a perfect balance of safety and economy.

The true character of the safety factor is disclosed by the introduction of a statistical concept of physical qualities, according to which the individual properties composing the structural phenomena of strain and resistance are represented by frequency distributions instead of by individual (minimum or maximum) values. The safety factor, correlating the strain induced with the resistance of the structure, may be derived from observable and measurable physical properties and phenomena.

The correlation of strain and resistance requires a careful analysis of all features of structural design, both from the points of view of the basic assumptions and of statistical interpretation. For the purpose of this analysis the available experimental and observational evidence is rather inadequate; the results obtainable at present, therefore, should be considered suggestive rather than conclusive. It is the insight gained into the essence of the safety factor that is of immediate practical interest.

The word "strain" in this paper is not to be confused with its conventional use to denote a linear measure or proportion of stretch. It has a meaning roughly equivalent to what is commonly called "stress," but is more general as it is intended to denote the mechanical effect of load, or external conditions on the structure, the structural member, or the section. The word "resistance" is a general term indicating "strength" or capacity to resist failure. It can be expressed in any units appropriate to the matter under discussion.

Popularity Index - 4.7%

Kimball, Bradford F., Assignment of Frequencies to a Completely Ordered Set of Sample Data. (Transactions, American Geophysical Union, 27, VI, pp. 843-846, December, 1946). 42

Abstract

It is pointed out that the problem of reaching an optimum fit of a cumulative frequency curve by analytical methods does not involve directly the assignment of either individual confidence intervals or individual frequencies to the observed values of the sample.

When one tests the nature of the function used to describe the behavior of the universe from which the sample be drawn, or the randomness of the observed sample, there may arise the occasion for the assignment of individual confidence intervals to each sample value. The assignment of a best reference point (such as a best frequency value) within a confidence interval, such as the mean, median, or mode, is shown to be subordinate to that of the assignment of a confidence interval.

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If, for purposes of graphical fitting, it is found desirable to assign a frequency to each sample value, the writer, in general, recommends the mean frequency of the mth ordered observation:

$$\hat{F}_m = m/(n+1)$$

In certain cases it may be possible to estimate frequencies of the mth values by

$$\hat{F}_m = F\left[E(x_m)\right]$$

independently of the unknown parameters, and such points might prove more desirable to use for graphical fitting near the extremes, if errors along the x direction are balanced out visually, relative to these points.

Popularity Index - 4.4%

Daniels, H. E., The Statistical Theory of the Strength of Bundles of Threads. (Proceedings Royal Society, London, 183, p. 405, 1945). 43

Abstract

A group of parallel threads of equal length, clamped at each end so that all threads extend equally under tension is called a bundle, and the maximum load which the bundle can support is called its strength. The object of the work is to study the probability distribution of the strength of bundles whose constituent threads are sampled randomly from an infinite population of threads in which the probability distribution of strength is known.

The relation between the strength of a bundle and the strengths of its constituent threads is first discussed, and results are stated for bundles so large that the proportions of threads of different strengths approach their expectations. The properties of the probability distribution of bundle strength are next developed in detail, attention being confined in the present paper to the case where all threads have the same load-extension curve up to breaking point. Finally, the asymptotic behaviour of the distribution for large numbers of threads is studied, and it is shown that in the commonest cases the distribution tends to assume the normal form.

Popularity Index - 4.4%

Gumbel, E. J., Simplified Plotting of Statistical Observation. (Transactions, American Geophysical Union, 26, I, August, 1945). 44

Abstract

The observed return-period of a value equal to, or larger than, the largest among n observations, called the occurrence-interval, is a function of n, and ought to be calculated from the most probable largest value, that is, from the formulas (7) and (8). For the usual distributions the occurrence-interval $T(\tilde{x}_n)$ converges toward n. This would not hold if we determine the occurrence-interval from the median or from the mean of the largest value. Condition (12) decides whether, with increasing n, the occurrence-interval decreases or increases toward the number of observations.

The adjusted frequencies $F(\hat{x}_m)$ of the m'th observation are obtained by linear interpolation between the probability $F(\tilde{x}_1)$ of the most probable smallest observation and the probability $F(\tilde{x}_n)$ of the most probable largest observation. This method, formula (30), leads to one, and only one, series of observations to be plotted on probability-paper and eliminates the use of exceedance- and recurrence-intervals.

The adjusted frequencies and return-periods for the floods are obtained from Table 1 and equation (30). The adjusted frequencies and return-periods for normal observations are obtained from Table 2 and equations (30') and (32). If the number of observations is at least 100, it is sufficient to use the asymptotic formulas (34) and (35).

Popularity Index - 4.4%

Lloyd, E.H., Least-Squares Estimation of Location and Scale Parameters Using Order Statistics. (Biometrika 39, pp. 88-95, 1952). 45

Abstract

In this paper we are concerned with distributions which depend on location and scale parameters only. For such distributions it will be shown that the parameters may be estimated by applying general least-squares theory to an ordered sample, the resulting estimates being unbiased, linear in the ordered observations, and of minimal variance. Explicit formulae are obtained for the estimates, and for their variances and covariance.

The special case of symmetrical distributions is discussed in some detail, and it is shown that for these the estimates are uncorrelated. As examples, the rectangular and the normal distributions are discussed; in the normal case the 'ordered' estimate of the mean turns out to be the sample mean, whereas in the rectangular case the ordered estimates of mean and range are functions of the extreme observations only, with sampling variances of order n^{-2}.

The 'ordered' estimate of the population mean has a sampling variance which never exceeds that of the sample mean; it is equal to that of the sample mean if and only if the row-totals of the variance matrix of the ordered observations all have the same sum. The 'ordered' estimate then becomes the sample mean itself. When the variance matrix does not satisfy this condition the 'ordered' estimate of the population mean has strictly smaller sampling variance than has the sample mean.

Popularity Index - 4.4%

Meyersberg, G., Effect of Volume and Surface on the Strength Properties of Material. (Acta Polytechnica, Physics-Applied Mathematics, 2, p. 2, 1952). 46

Popularity Index - 4.4%

Tucker, Jr., John, Effect of Dimensions of Specimens upon the Precision of Strength Data. (Proceedings ASTM, 45, p. 952, 1945). 47

Abstract

Statistical theories on the strength of materials are applied in estimating the effects of change in a dimension of the specimen on the mean strength and on the dispersion of the strength within a group of like specimens. The weakest-link theory predicts the effects of an increase in the length of specimens subjected to tension, compression, flexure, or torsion and in the depth of specimens subjected to flexure. The strength-summation theory appears to predict reasonably well the effects of an increase in the cross-sectional areas of specimens subjected to tension or compression and of an increase in width of the flexural specimen. Analyses based on the statistical theories of strength and the results of some tests indicate that reliable measures of the strength and uniformity of the strength of concrete may be obtained by testing a larger number of specimens which are much smaller than those commonly used.

Popularity Index 4.0%

Weibull, W., Investigations into Strength Properties of Brittle Materials. (Ingeniorsvetenskapsakademiens, Handlingar NR 149, 1938). 48

Abstract

By measuring that force which is required to produce cracks in a glass plate subjected to the pressure of steel balls of various diameters, it was found that the ultimate strength to a high degree depends on the rate of application of load, and that the relation between the breaking load and the rate of load application may be expressed by a linear extrapolation formula. It is furthermore shown that if the glass plate is contiguous to certain electrolytes, the ultimate strength may in some cases increase more than 100 percent. Finally, an experimental verification is given of a law set up by Auerbach and stating that the ultimate strength is direct proportional to the ball radius, and not to the square of the ball radius, as required by the classical theory of strength.

An examination of the ultimate strength in the case of two-dimensional state of stress in glass and bakelite plates shows that the ultimate strength of these materials is in all probability determined by the maximum tensile stress, and not by the shearing stress or the shear stress energy.

Popularity Index - 3.8%

Kontorova, T.A., and Timoshenko, O.A., A Generalized Statistical Theory of Strength in the Case of the Nonuniform Stress State. (Journal of Technical Physics, 19, 3, p. 355, 1949). 49

Popularity Index - 3.7%

Wilks, S.S., Order Statistics, (Bulletin American Mathematical Society, 54, pp. 6-50, 1948). 5

Abstract

It is the purpose of this paper to present some of the more important results in the sampling theory of order statistics and of functions of order statistics and their applications to statistical inference together with some reference to important unsolved problems at appropriate places in the paper. The results will be given without proofs, since these may be found in references cited throughout the paper.

Popularity Index - 3.4%

Downton, F., Least-Squares Estimates Using Ordered Observations. (Annals of Mathematical Statistics 25, pp. 303-316, 1954). 51

Abstract

The purpose of this paper is to compare for various two-parameter distributions, of the form $f\{(x-\mu)/\sigma\}/\sigma$, the estimates of the parameters obtained by applying the method of least squares to the observations, after these have been arranged in order of magnitude. Estimates obtained by this process we shall call "ordered least-squares estimates." Such estimates are unbiased and have minimal variance among all unbiased estimates which are linear in the ordered observations.

This estimation process has been previously discussed by Godwin (1) and (2) and Lloyd (3). In the present paper, ordered estimates are obtained explicitly for a class of two-parameter distributions having the above form. This class contains the rectangular and the right triangular distributions as special cases. It also reduces to the exponential distribution as a limiting case. Other special cases of this class of distributions have also been previously discussed by Craig (4).

Further, a general property of ordered least-squares estimates of the parameter λ in distributions of the type $f(x/\lambda)/\lambda$ is discussed. As a result it is shown that the ordered least-square estimate of the scale parameter in the Pearson Type III distribution is identical with the maximum likelihood estimate.

Popularity Index - 3.4%

Kies, J.A., The Strength of Glass. (Ballistics Branch, Mechanics Division, Naval Research Laboratory, Washington, D.C., April, 1958). 52

Abstract

A new statistical model is proposed for representing the effect of flaws on the breaking strength of specimens in which an upper strength limit exists. Strengths at chosen levels of probability for failure are emphasized rather than average strengths. For samples of sufficiently small size and high strength the new model has a practical advantage. For sufficiently large size specimens having strengths negligible in comparison with the upper limiting strength the Weibull function is adequate and more convenient. Tests on fibers at NRL and elsewhere illustrate the usefulness of the new formula. Some results of test made elsewhere on massive glass show the value of basing design stress on the indicated strength for an

arbitrarily chosen low probability of failure rather than on the average strength. Tempered glass appears to have far greater advantage on this basis than when average strengths are compared. Statistical and simple experimental models are proposed for use in studying the relation between the strength of fibers and the strength of laminates made from them.

Popularity Index - 3.3%

Tye, W., Factors of Safety - Or of Habit? (Journal of Royal Aeronautical Society, 1944). 53

Abstract

Our engineering habits form slowly, and once formed are slow to change. This is perhaps less true in aeronautics than in other branches of engineering. Nevertheless some aeronautical customs are deeply rooted, so much so that it is easy to confuse the superstructure of habit with the basic foundations. In this article I have reviewed some of the customary methods of specifying strength conditions and have tried to disentangle the underlying principles. Current changes in these methods emphasize the need of a proper appreciation of the principles, and a study of these principles suggests even more radical changes of methods in future.

In a brief article it is impossible to cover the whole field of strength requirements. To give a focus to the argument, I have confined this article to discussion of the main "symmetrical flight manoeuvres," but the general theme is equally applicable to any kind of loading condition. The symmetrical flight manoeuvres are those flight manoeuvres which result from an action on the part of the pilot (thus excluding loading due to atmospheric gusts) and which involve motion in the pitching plane only (thus excluding rolling, spinning, yawing, etc.). In such a manoeuvre the loads sustained by the aeroplane are primarily dependent on the speed of flight and the acceleration of the aeroplane normal to its flight path.

Popularity Index - 3.2%

Tucker, Jr., John, Statistical Theory of the Effect of Dimensions and of Method of Loading upon the Modulus of Rupture of Beams. (Proceedings A.S.T.M, 41, p. 1072, 1941). 54

Abstract

There is an inherent difference in the strength of duplicate test specimens no matter how carefully these specimens are made or tested. Such differences are a natural characteristic of the materials and are more pronounced in some than in others. The paper shows how the variations in

the strength of small elements of volume within a specimen will affect the modulus of rupture of beams of different dimensions and beams subjected to different loading. For example, the modulus of rupture of a beam will be decreased with beam length and with beam depth and will be greater in centrally loaded beams than in similar beams loaded at third points.

Popularity Index - 3.1%

Lieblein, Julius, and Salzer, Herbert E., Table of the First Moment of Ranked Extremes. (Journal of Research of the National Bureau of Standards, Vol. 59, No. 3, Research Paper 2787, September, 1957). 55

Abstract

Let a sample in n independent random values from the extreme-value distribution, with c.d.f. $\Phi(y) = \exp(-e^{-y})$, be arranged in decreasing order and denoted by $y_1, y_2, \ldots, y_m, \ldots, y_n$. The table gives the expected values for all these order statistics for sample size not exceeding 25. For the larger samples, up to n = 100, the expected values are given only for the first 26 largest values.

Popularity Index - 2.9%

Duckworth, W.H., Schwope, A.D., Salmassy, O.K., Carlson, R.L., and Schofield, H.Z., Mechanical-Property Tests on Ceramic Bodies. (Wright Air Development Center Technical Report No. 52-67, March, 1952). 56

Abstract

The fracture of brittle-state materials, primarily brittle ceramics, was studied. The principles for the selection, evaluation, and design of brittle materials from a statistical or probability viewpoint were set forth.

The distribution curve of fracture stresses was found to give an adequate description of the strength of a brittle body under a given set of conditions.

The mean fracture stress of a brittle body was found to be inadequate for the design of a brittle structure.

The factors influencing the fracture of brittle ceramic materials were studied, including the effects of size, stress state, strain rate, and delayed fracture, temperature, and flaws.

The entire distribution curve of fracture stresses was indicated to be a function of the size and stress state of a brittle body. All the materials investigated, glass, porcelain, nickel-bonded titanium carbide, plaster of Paris, and embrittled steel showed the same qualitative effect of size and stress state.

Weibull's statistical theory of strength predicted the effect of size, and the effects observed in the simple stress states of tension, bending, and torsion. Weibull's theory was not adequate, however, for predicting the effects of combined stresses.

The research indicated that static-fatigue data will require statistical analysis before they are safe for use in the design of certain ceramics under sustained loads. The materials studied exhibited an increase in strength with increasing strain rate.

Popularity Index - 2.8%

Dodd, Edward Lewis, The Greatest and the Least Variate under General Laws of Error. (Transactions American Mathematical Society, 25, pp. 525-539, 1923). 57

Popularity Index - 2.6%

Potter, W.D., Simplification of the Gumbel Method for Computing Probability Curves. (U.S. Department Agriculture Soil Conservation Service, Technical Publication 78, U.S. Government Printing Office, May, 1949). 58

Abstract

Hydraulic structures to control surface runoff from large dams to small terrace outlet channels are so designed that their capacities may be expected to be exceeded once in some specified period. The length of this period depends on the cost of the structure and the extent of damage that would result from its failure. For the large dam where a failure might entail the loss of property valued in the millions of dollars, this period might be a thousand years. For smaller structures, such as the terrace outlet channel, where property damage due to failure would be relatively small, the frequency of such failures might be once every 10 years. To be

of maximum use, therefore, to engineers and field technicians, much of the analysis of hydrologic data should be expressed in terms of recurrence intervals. Peak rates and amounts of surface runoff or amounts and intensities of rainfall can be expressed in values that might be expected to be equaled or exceeded with some specified frequency. Likewise, reduction in peak rates or amounts of surface runoff that might be expected as a result of improved land use can also be expressed in terms of frequency. This type of analysis involves the frequent use of probability curves. For the Gumbel method of computing such curves, it is believed that much time can be saved by the use of the relationships and graphs developed in this study.

Popularity Index 2.4%

Kimball, Bradford.F., The Bias in Certain Estimates of the Parameters of the Extreme-Value Distribution. (Annals of Mathematical Statistics, 27, pp. 758-767, 1956). 59

Abstract

This paper is mostly concerned with a modification of the maximum-likelihood estimate of the scale parameter of the extreme-value distribution for which the bias can be explicitly obtained. A formula for computing this bias is derived, and bias factors are tabulated for sample sizes from n = 2 to n = 112. A brief comparison is made between this estimator and the optimum linear estimator for a sample of size n = 6. Attention is called to a bias which results from the maximum-likelihood estimate of the second parameter, and formulas for the bias and the variance of this estimate are obtained. In the concluding section, the significance of certain aspects of the maximum-likelihood estimate of the scale parameter in practical applications is briefly discussed.

Popularity Index - 2.4%

Sarhan, A.E., and Greenberg, B.G., Estimation of Location and Scale Parameters by Order Statistics from Singly and Doubly Censored Samples. (Annals Mathematical Statistics, 27, pp. 427-451, 1956). 60

Abstract

The normal distribution up to samples of size 10.

Popularity Index - 2.2%

Gumbel, E. J., Floods Estimated by Probability Method. (Engineering News-Record, 134, pp. 97-101, 1945). 61

Abstract

Defining a flood for mathematical purposes as the largest daily discharge observed in a 365-day period and considering flood as an unlimited statistical variable, the author utilizes the theory of probability to estimate future floods. The probability of a flood equal to or less than a certain magnitude is expressed by a formula, but to facilitate the application of the theory a special probability plotting paper is used. However, since there is no plotting position on probability paper for zero or one, in order to plot the entire series of observations, it is suggested that the plotting positions be based on the probabilities of the most probable floods. The procedure is demonstrated for the floods of the Mississippi River as recorded at Vicksburg from 1890 to 1939. The author, a graduate of the Universities of Munich and Berlin, formerly was professor of statistics at the Universities of Heidelberg, Germany, and Lyon, France, and lecturer at the Henri Poincare Institute, University of Paris.

Popularity Index - 2.2%

Gumbel, E. J., On the Frequency Distribution of Extreme Values in Meteorological Data. (Bulletin of the American Meteorological Society, 23, 3, pp. 95-105, March, 1942). 62

Abstract

The four methods of comparison lead to a satisfactory fit between theory and observation. The best agreement is obtained for the precipitation. The goodness of fit diminishes of course with the number of observations. The agreement is not so good as the fit obtained for the classical Gaussian, Poisson, and exponential laws. But if we take into account, that neither the number of observations N from which we draw the extreme values, nor the number of years under observation n, are large, and that the measurements might not be sufficiently precise, we can consider the theory as a satisfactory explanation of the observations. The return period can safely be used for obtaining the order of magnitude of future extreme values. It is only from more accurate data and from longer series of observations that we can decide whether the divergences between theory and observations which we met in our examples are fully explained by the reasons given above, or whether specific circumstances, such as interdependence, periodicity, or inhomogeneity create conditions which fall outside of our scheme.

Popularity Index - 2.2%

Tucker, Jr., John, The Maximum Stresses Present at Failure of Brittle Materials. (Proceedings ASTM, 45, p. 961, 1945). 63

Abstract

It is shown by a statistical theory of strength how stresses with magnitudes much beyond those usually considered as the strength of the material may be present in a portion of a test specimen. It is theoretically demonstrated that the modulus of rupture as usually calculated should be much greater than the tensile strength. Analysis demonstrates that the load at failure of a cement briquet does not have a fixed ratio to the tensile strength of the material. It is also shown that in a concrete cylinder tested in compression, with ends restrained against lateral expansion, the tensile stresses present in a small portion of the volume are too small to cause a tensile failure.

Popularity Index - 2.1%

Pugsley, A.G., Structural Safety, (Journal of Royal Aeronautical Society, June, 1955). 64

Popularity Index - 2.1%

Salmassy, O.K., Duckworth, W.H., and Schwope, A.D., Behavior of Brittle-State Materials. (Battelle Memorial Institute, WADC Technical Report 53-50, Part 1, Materials Laboratory, Contract No. AF 33(038)-8682, Project No. 7350, Wright Air Development Center, Air Research and Development Command, U.S. Air force, Wright-Patterson Air Force Base, Ohio). 65

Abstract

The factors influencing the fracture of brittle ceramic materials were studied; the effects of size and stress state were given primary consideration. In addition, initial consideration was given to the effects of strain rate and temperature.

The strength of plaster of Paris was found to decrease with an increase of size in the simple stress states of tension, compression, bending, and torsion. Initial analyses indicated that Weibull's statistical theory of strength could be used to predict the observed effects of size and stress state on the strength of plaster.

The effects of combined stresses on the fracture strength were studied by means of tests conducted on cylinders of plaster subjected to internal pressure and axial loading. Initial analyses of data from these combined-stress tests indicated that fracture data could be analyzed using the elastic theory of thick-walled cylinders.

The effect of superposed bending stresses on tension-test data was analyzed using Weibull's theory. This analysis indicated that superposed bending stresses should increase the observed tensile strength of a brittle material. Tension data on plaster agreed qualitatively with this prediction.

Analysis of the standard compression test indicated that fracture data from this type of test were unreliable and that the standard compression test could not be used in a research program where precise quantitative fracture data were required.

Exploratory studies were made of the effect of varying the strain rate or the stress rate on the fracture of plaster of Paris. These studies indicated a decrease of fracture stress with increased rates of loading, an effect opposite to that reported in the literature for other brittle materials. The relation between the effects of rate of loading and stress duration (static fatigue) was considered.

Popularity Index - 2.0%

Holland, A.J., and Turner, W.E.S., The Effect of Width on the Breaking Strength of Sheet Glass. (Journal of the Society of Glass Technology, 20, p. 72, 1936). 66

Abstract

A more detailed study than in our previous paper has been made of the effect of width on the modulus of rupture of strips of 26 oz. sheet glass varying from approximately 0.4 to 1.2 cm. in width, the sides of the strips being in different cases (a) ground and mechanically polished, (b) ground and mechanically polished followed by fire polishing, (c) cut with the diamond and tested with the residual flaws in tension. Progressive increase in the modulus of rupture was found with diminution in width. For fire finished strips of 0.395 cm. width, values as high as nearly 1700 kg./cm. were obtained, the mean being 1299.

It was demonstrated that the Karmarsch equation relating the strength (F) of metallic wires to their diameter d, namely,

$$F = a + \frac{b}{d}, \text{ where}$$

a and b are constants, applies equally well to our results in which d is regarded as the width of the specimen. From Griffith's modified equation, values for the "ultimate strength" of glass were calculated.

Straight fractures were consistently obtained for widths of 0.7 cm. (and, in general, below 0.8 cm.) when the sides were not fire polished. In the latter condition more complex fractures were either usual or at least frequent even for specimens of 0.4 cm. width.

Popularity Index - 2.0%

Smekal, Professor A., The Influence of Specimen Width on the Breaking Strength of Sheet Glass. (Communicated to the General Discussion of Technical Group II at the International Congress on Glass, July 9, 1936). 67

Abstract

A logarithmic equation is proposed to express the results obtained by A.J. Holland and W.E.S. Turner on the variation of the bending strength of sheet glass strips with different specimen widths.

Popularity Index - 1.9%

Press, Harry, The Application of the Statistical Theory of Extreme Values to Gust-Load Problems. (Report 991, Langley Aeronautical Laboratory, Langley Field, Virginia, November, 1949). 68

Abstract

An analysis is presented which indicates that the statistical theory of extreme values is applicable to the problems of predicting the frequency of encountering the larger gust loads and gust velocities for both specific test conditions as well as commercial transport operations. The extreme-value theory provides an analytic form for the distributions of maximum values of gust load and velocity. Methods of fitting the distribution are given along with a method of estimating the reliability of the predictions.

The theory of extreme values is applied to available load data from commercial transport operations. The results indicate that the estimates of the frequency of encountering the larger loads are more consistent with the data and more reliable than those obtained in previous analyses.

Popularity Index - 1.7%

Richards, Cedric, W., Size Effect in the Tension Test of Mild Steel. (Proceedings ASTM, pp. 995-1002, 1954). 69

Abstract

In 1931 Fujio Nakanishi made his well-known report of a yield point in bending raised by 50 percent above that in tension, using rectangular beams of mild steel. The presence of a size effect seems to offer the only satisfactory explanation for this and subsequent widely divergent results that have been reported over the past twenty-odd years. The investigation described herein has for its objects the development of an adequate theoretical basis for such a size effect and the testing of its validity by experiment. Due to a similarity between the discontinuous yielding of mild steel and brittle fracture, Weibull's Statistical Theory of the Strength of Materials has been adapted to fit the new problem. Because of its statistical nature, large numbers of tests are required to check the theory. The present report covers the first series of tests, which were made in tension. The experimental results obtained demonstrate a definite dependence of the upper yield point of mild steel on specimen size. Thus the conclusion is reached that in the tension test of mild steel the specimen size is one of the important variables.

Popularity Index 1.7%

Volkov, S.D., A Single Statistical Theory of Strength of Solid Bodies. (Journal of Technical Physics, 24, 12, p. 2250, 1954). 70

Abstract

Single mechanism of microscopic destruction under the action of tensile forces (after Yakutovich) taking into account the condition of microscopic destruction and the effect of change of resistance of microscopic destruction under the action of connecting resistances in the process of plastic deformation (after Davidenko and Stepanov) one utilized for the building of boundaries of cohesive destruction. It is proposed, that the modulus of distribution of microscopic resistances is dependent only on the energy of deformations and the solidity of distribution of resistance to destruction has a sharp maximum.

Popularity Index - 1.5%

Cameron, J.M., Tables for Constructing and for Computing the Operating Characteristics of Single-Sampling Plans. (Industrial Quality Control, pp. 37-39, July, 1952). 71

Abstract

This note presents tables for computing the operating characteristics of single-sampling plans and for constructing sampling plans having desired operating characteristics.

Popularity Index - 1.4%

Mugele, R.A., and Evans, H.D., Droplet Size Distribution in Sprays. (Industrial and Engineering Chemistry, 43, 6, pp. 1317-1324, June, 1951). 72

Abstract

General features of size distribution are reviewed for dispersed systems. The concepts of "mean diameter" and "distribution parameter" are clarified and generalized. Previously applied distribution equations (Rosin and Rammler, Nukiyama and Tanasawa, log-probability) are examined critically in regard to theoretical soundness, and application to spray data.

A new equation, called the upper-limit equation, is formulated and proposed as a standard for describing droplet size distributions in sprays. It is based on the differential equation of the "normal" or Gaussian distribution, the distributed quantity being $y = \ln ax/(x_m - x)$ where a is a dimensionless parameter, x is droplet diameter, and x_m is maximum stable diameter.

The upper-limit equation is applied to a wide variety of experimental data on sprays and more limited results on other dispersoids. It is concluded that the new equation fits the available spray data accurately, calculates the mean diameters accurately, applies also to emulsions and aerosols when the mechanism of formation is not too different from that of sprays, and indicates the type of distribution function that may be derivable from the basic mechanism of dispersion, when this mechanism is better understood. For a mechanical spray, the relation of the parameters of the distribution equation to physical properties and design variables is indicated.

Popularity Index - 1.4%

North, J.D., Some Aspects of the Relationship between Airworthiness and Safety. (Journal of Royal Aeronautical Society, 53, p. 915, 1949). 73

Abstract

The purpose of this paper is to attempt to examine the relations between airworthiness and safety.

Popularity Index - 1.4%

Pugsley, Professor Sir Alfred, Design for Safety and Efficiency. (Structural Engineering, 35, p. 36, 1957). 74

Abstract

This paper is devoted largely to two related lines of research and development affecting the safety and efficiency of modern structures. These lines of work had their origins in the First World War and are even now only approaching a stage at which they can have much impact on structural design. It will be convenient in the first instance to discuss structural efficiency and structural safety separately, though, of course, our ideas and customs relating to both are very much interwoven.

Popularity Index - 1.3%

Weibull, W., A Statistical Analysis of the Size of Cyrtoidea in Albatross Cores from the East Pacific Ocean. (Nature, No. 4181, p. 1047, December 17, 1949). 75

Abstract

Some years ago, I introduced a new statistical distribution function for the description of the strength properties of materials. Recently, this function has been used for the statistical representation of fatigue failures in solids. Meanwhile, I have applied it to a number of distribution problems in different fields, in many cases with a surprisingly close agreement.

Popularity Index - 1.1%

Afanas'yev, N.N., The Statistical Theory of Strength Fatigue. 76
(Journal of Technical Physics, 10, 19, p. 1553, 1940).

Popularity Index - 1.1%

Nordquist, John M., Theory of Largest Values Applied to Earthquake Magnitudes. (Transactions, American Geophysical Union, 26, 1, pp. 29-31, August, 1945). 77

Abstract

The theory of largest values requiring data on only the largest event in each of a number of equal time-intervals, recommended itself to the author as a possible way of describing the earthquake activity of a region. A preliminary analysis using the calendar month as the interval having demonstrated the applicability of the theory in this field, the author has investigated the feasibility of using still shorter intervals. In the present paper the interval used is one-third of a month--the first day through the tenth, the eleventh through the twentieth, and the twenty-first to the end of the month. This interval therefore corresponds to that of one year used in flood-analyses. A compensating change has been made in the return-period scale. Incomplete results of further analysis indicate that it is feasible to use a time-interval as short as five days.

Popularity Index - 1.0%

Koshal, Ram Saran, and Turner, A. James, Studies in the Sampling of Cotton for the Determination of Fibre-Properties. 78
(Transactions, The Journal of the Textile Institute, 21, pp. 325-370, 1930).

Abstract

Part I - Introductory and Experimental. It is pointed out that for the determination of the value of any fibre-property of a cotton, a small sample has to be selected for the experiment. Three questions, therefore, arise, viz. - (1) How we may obtain a satisfactory sample, (2) how many fibres constitute a satisfactory sample, (3) what is the degree of reliability of the results obtained for the value of a fibre-property? The present investigation has therefore been undertaken primarily with a view to obtaining satisfactory answers to these three questions for the following fibre-properties - length, width, number of convolutions, strength, and

rigidity. The tests of these properties have been made on some 3,000 fibres of Surat 1027 A.L.F., 1926-26; the description of these tests and the discussion of the results is divided into four parts, the first two parts forming the present paper. Part I is introductory, and contains also a description of the experimental methods used for the measurement of the fibre-properties; Part II deals with the frequency-curves for the various fibre-properties; Part III will deal with the three questions of sampling in the light of the results discussed in Part II; and Part IV will deal with the inter-relationship of the different fibre-properties.

Part II. Frequency-Curves for various Fibre-Properties. The answers to the questions formulated in Part I depend upon the manner of distribution of the test-values. Frequency - polygons are drawn to indicate the various frequency-distributions. But as the results obtained relate only to comparatively small samples, theoretical continuous frequency-curves have been drawn by a recognized method to give the closest possible degree of fitting to the frequency-polygons. It is found that the frequency-distributions for fibre-length and convolutions are moderately symmetrical and nearly normal; for fibre-width, symmetrical and practically normal; for fibre-strength, moderately asymmetrical; and for fibre-rigidity, extremely asymmetrical. The causes of the asymmetrical distributions of fibre-strength and fibre-rigidity are discussed at some length and are finally ascribed either to a change in the external conditions of growth during the life-history of the plant, or to the mutual interference of the fibres under the ordinary conditions of their growth.

An appendix is given explaining various statistical terms and methods used in curve-fitting, with detailed examples of their applications to fibre-properties.

Popularity Index - 1.0%

Pitman, E.J.G., The Estimation of the Location and Scale Parameters of a Continuous Population of Any Given Form. (Biometrike, 30, pp. 391-421, 1939). 79

Abstract

The main problem considered is the location and scaling of the distribution of a continuous chance variable X. We suppose that the probability function of X is

$$\frac{1}{c} f\left\{\frac{x-a}{c}\right\}, \quad c>0,$$

where the function f(x) is known but one or both of the parameters a, c, which determine respectively the location and scale of the distribution, is unknown. We have a sample of n independently observed values of X, and

from these we have to estimate the unknown parameter or parameters. Any function of the sample values whose value may be used as an estimate of an unknown parameter is called an estimator of that parameter. The paper shows how to determine an estimator with any required property, such as minimum mean absolute error, or minimum mean square error. In particular, the closest estimator is determined; this is an estimator whose median value is the true value of the parameter and which is likely to be closer to the true value than any other estimator. It is shown that in certain cases a best estimator exists.

Fiducial limits for the unknown parameter are determined, and what is called the fiducial distribution of the parameter is defined. It is shown that problems of estimation can be dealt with very simply, and completely, by means of fiducial distributions. For a population of any given form, the fiducial distribution of a when both a and c are unknown, provides us with a test which corresponds to "Student's" test for significance of the mean of a sample from a normal population.

The estimation of the difference between the location parameters of two populations of similar forms is discussed.

Popularity Index - .9%

Campbell, George A., Probability Curves Showing Poisson's Exponential Summation. (Bell System Technical Journal, pp. 95-113, 1923). 80

Popularity Index - .9%

Kluyver, Professor J.C., A Local Probability Problem. (Proceedings Nederlands Akad. Wetensch 8, pp. 341-350, 1906). 81

Popularity Index - 0%

Bartlett, M.S., Fitting a Straight Line when Both Variables are Subject to Error. (Biometrics, 5, pp. 207-212, September, 1949). 82

Abstract

A simple method of fitting a straight line when both variables are subject to error was examined by Wald in 1940. The purpose of the present note is to present and illustrate a modification of Wald's method having the advantage in general of greater accuracy. Before any detailed exposition

it will be well to recall two important points:

(i) a distinction must be made between the linear regression equation of a variable y on a second variable x, and a linear functional relation between two variables Y and X masked by errors. The former equation is still available for prediction even if the variable x is subject to error, but is not necessarily appropriate for a functional relation when one exists.

(ii) it is possible to set up maximum likelihood equations for the second problem, but they do not lead to a unique solution without further assumptions, such as an assumption about the relative magnitude of the errors in x and y.

These points have been emphasized by many previous writers, for example, by Wald or more recently by Lindley. In view of (ii) it is useful to consider, in the common case when the observations have equal weight, the following elementary method:

(a) For the location of the fitted straight line use as one point the mean coordinates $\bar{x}$, $\bar{y}$, just as in the least-squares method.

(b) For the slope, first divide the n plotted points into three groups, the equal numbers k in the two extreme groups being chosen to be as near n/3 as possible (the three groups are non-overlapping when considered, say, in the x direction). The join of the mean coordinates $\bar{x}_1$, $\bar{y}_1$, and $\bar{x}_3$, $\bar{y}_3$ for the two extreme groups is used to determine the slope.

Popularity Index - 0%

Bartoo, James B., Elementary Statistical Concepts. (Proceedings, Statistical Methods in Materials Research, Pennsylvania State University, 1956). 83

Abstract

This paper is intended to give a survey of the more important statistical tools which might prove useful to engineers engaged in materials research. It is not intended to be complete. Details of the various methods may be found in the references cited.

Popularity Index - 0%

Blom, Gunnar, On Linear Estimates with Nearly Minimum Variance. (Arkiv For Matematik, Band 3, nr 31, 1956). 34

Abstract

Let z be a random variable with a continuous cumulative distribution function $[F(z-\mu)/\sigma]$ which depends upon two unknown parameters μ and σ. Consider an ordered random sample

$$z_{(1)} \leq z_{(2)} \leq \cdots \leq z_{(n)}$$

of z-values. If the means and covariances of the reduced order statistics

$$x_i = \frac{z_{(i)} - \mu}{\sigma} \qquad (i = 1, 2, \ldots, n)$$

are known, it is possible to find linear unbiased minimum variance estimates

$$\sum_{i=1}^{n} g_{1i} z_{(i)} \qquad \text{and} \qquad \sum_{i=1}^{n} g_{2i} z_{(i)}$$

of μ and σ respectively (Lloyd, 1952). These estimates may be called best unbiased estimates. A serious drawback of the solution is that in most cases it involves very time-consuming numerical calculations.

The object of this paper is to show that, under general conditions, it is possible to find a convenient approximation to the best solution which may be termed a nearly best unbiased estimate. The variance of this estimate is, as some examples will show, often very little in excess of the minimum variance. The method presupposes that the means (but not the covariances) of the variables x_i are known.

By a slight modification of the method it may be used also when neither the means nor the covariances are known. The resulting estimates will be called nearly best, nearly unbiased estimates.

Both types of estimates mentioned above may be derived from a theorem given in the next section.

Popularity Index - 0%

Boyes, William E., The Practicality of Predicting Reliability Numbers. (Sandia Corporation Reprint, SCR-157, from Proceedings Sixth National Symposium on Reliability and Quality Control in Electronics, p. 282, January 11-13, 1960). 85

Abstract

This discussion begins with differentiating between prediction, prognostication, and foretelling by stating that "reliability" now lies in the middle field. The formulae and fact required for scientific prediction are

not adequate, yet trends and basic principles are sufficient to indicate futures and to guide decisions. The practice of a specialist conducting an a priori reliability analysis, including estimated reliability numbers, is defended on the basis that the predictions are valuable guides and that the best foresight is vested in those who have examined all available test data and have the training and orientation to understand its meaning in the system under study. The lack of adequate scientific laws is admitted and appropriate cautions are offered. Reliability is therefore considered as a problem in prediction with a philosophy and simple model being offered. In particular, the need for establishing the correlation or degree of simulation between any test used as a reliability predictor and the ultimate use is described.

Popularity Index - 0%

Calvert, R. L., Some Notes on the Estimation of Reliability. 86
(Sandia Corporation Reprint, SCR-5, Published in Joint Military-Industry Guided Missile Reliability Symposium, October, 1956).

Abstract

The purpose of this paper is to show the value of complete success-failure history of past accepted lots of an equipment or component in deriving estimates of f, the fraction successful in a lot presented for use. When sufficient past lot information has accumulated, it is possible to determine a density function g(f). The use of this density function with or without a sample from a future lot L allows certain estimates of the success probability to be made for units drawn from that lot. Obviously, it must be assumed that lot L will see the same spectrum of environments that has been applied to past lots.

The number of lots for which complete success-failure history is required depends on the test which is applied to determine the "goodness-of-fit" of the g(f) which is chosen to fit the data. This last subject is not discussed in this paper.

Popularity Index - 0%

Coleman, Bernard D., Time Dependence of Mechanical Breakdown Phenomena. (Journal of Applied Physics, 27, 8, pp. 862-866, August, 1956). 87

Abstract

A phenomenological theory of the time dependence of mechanical breakdown phenomena is presented which is applicable to creep failure of

oriented polymeric filaments under tensile stresses. In using the theory, one makes assumptions about the distribution of breaking times in ensembles of filaments which are bearing constant loads, and then proceeds to calculate the distribution of lifetimes under other stress histories, e.g., loads increasing linearly with time and sinusoidal loads. The a priori assumptions used here permit a calculation of the dependence of observed tensile strengths on both the sample size and the rate of loading. Experiments involving drawn 66 nylon monofilament yarn are cited to illustrate how the parameters which describe the average lifetime under dead load behavior of a yarn may be used to calculate its tensile strength distribution when measured with a constant rate of loading apparatus.

Popularity Index - 0%

Duckworth, Winston H., Designing with Brittle Materials. 88
(Materials in Design Engineering, pp. 82-85, January, 1959).

Abstract

Conventional mechanical design principles cannot be applied with confidence to brittle materials such as ceramics. In designing with ductile metals, laboratory-determined yield strength values plus a selected safety factor provide a safe structural design. With ceramics, which have no yield point and fail in a brittle manner, no alternative to trial-and-error design exists. A successful mechanical design with brittle materials is more likely, however, if certain considerations are properly understood. These considerations lie in the areas of (1) component design, (2) property data, and (3) material quality.

Adjusting component design. The problem of brittle failure in any given ceramic design can be minimized in several ways. Each way tends to make the material fail by deformation rather than brittle fracture, if overloaded.

Popularity Index - 0%

Grab, Edwin L., and Savage, I. Richard, Tables of the Expected 89
Value of 1/X for Positive Bernoulli and Poisson Variables.
(American Statistical Association, 49, pp. 169-177, 1954).

Abstract

The random variable X is said to have a positive Bernoulli distribution (11) if the probability that $X = x$ is equal to

$$\binom{n}{x} p^x q^{n-x} (1 - q^n)^{-1}$$

for $x = 1, 2, \ldots, n$ where $q = 1-p$ and $0 < p \leq 1$. Similarly the variable X is said to have a positive Poisson distribution if the probability that $X = x$ is equal to $e^{-m}(1 - e^{-m})^{-1} m^x/x!$ for $x = 1, 2, \ldots$, and $m > 0$.

Table I gives the values of $\mathbf{E}(1/X \mid n, p)$ to five decimal places where

$$\mathbf{E}(1/X \mid n, p) = (1 - q^n)^{-1} \sum_{x=1}^{n} \binom{n}{x} x^{-1} p^x q^{n-x} \qquad (q = 1 - p) \qquad (1)$$

for the following values of the parameters:

$n = 2(1)20;\ p = .01, .05(.05).95, .99$

$n = 21(1)30;\ p = .01, .05(.05).50.$

Table II gives values of $\mathbf{E}(1/X \mid n)$ to five decimal places, where

$$\mathbf{E}(1/X \mid m) = e^{-m}(1 - e^{-m})^{-1} \sum_{x=1}^{\infty} m^x/(x!x),$$

for the following values of the parameter:

$m = .01, .05(.05)1.0(.1)2.0(.2)5.0(.5)7.0(.1)10(2)20.$

Popularity Index - 0%

Guard, R. W., Multi-Factorial Experiments in Materials Development. (Proceedings Statistical Methods in Material Research. Pensylvania State University, 1956). 90

Abstract

In developing new and improved materials, the important things are timing of the development and the cost required to develop the optimum alloy composition, together with the optimum treatment. For this reason the engineer should use all means at his disposal to do his experimentation as efficiently as possible and to reduce the chance that he might have missed a good material. There are several techniques which are available for experimentation in this area and for designing a set of experiments to find the best material.

The basic work in experimental designs has been done in agriculture, and since agricultural production differs quite considerably from engineering production, there are several things about the use of experimental designs in engineering which are different from those in agriculture. First, of all, it is obvious that in engineering development we can do experiments much more rapidly and it is not necessary to wait through a growing season which may be a year or two before getting results. This means

that we can use simple designs, because there is not the necessity of getting all of the answers the first time--or wasting a whole year. This higher speed also means that we can use sequential tests in which we do the experimentation in stages and use the information obtained from the first stage for subsequent experiments.

Popularity Index - 0%

Head, J.W., and Oulton, G.M., Fitting Curves to Experimental Data by Least Squares. (Aircraft Engineering, pp. 268-270, September, 1957). 91

Abstract

An examination of the method of plotting experimental results. We here suppose that we have a number n of experimentally derived pairs of corresponding values of an independent variable (x) and a dependent variable (y). We have reason to expect that a known function Y of x and y is a polynomial in some other known function X of x and y. For a polynomial of given degree n, the least-squares technique for determining the coefficients is well known; here we show geometrically how the goodness of fit is affected when n is raised from 1 to 2, the number n of given pairs of corresponding points being 5. The results suggest that the five points are not usually placed so that the fit is appreciably better for n = 2 than for n = 1, and that it is seldom useful to attempt to fit any non-linear curve to experimental results.

Popularity Index - 0%

Homes, Georges A., and Gouzou, Jacques. Contribution to the Study of the Mechanisms of Fracture of Metals. (Revue de Metallurgie XLVII, No. 9, pp. 678-692, 1950). 92

Popularity Index - 0%

Irwin, G.R., The Effect of Size upon Fracturing. (ASTM Special Technical Publication, 158, pp. 176-194, 1954). 93

Abstract

It is concluded that a fracture size effect in ductile metals is necessarily present because of the tendency of work of fracturing to approach proportionality to fracture area as the fracture deepens. In

addition, formation of the initial starting crack occurs at a smaller overall strain the larger the test specimen size. This latter feature is of special importance under testing conditions such as those of low temperature and of notched bend testing in which fracture instability occurs, if at all, at very early stages of fracture extension. A greater frequency of sudden fracturing for large as compared to small test specimens is the theoretically predicted normal expectation. The fracture size effect of brittle materials can be represented as if they were the result of a statistical distribution of flaws as was proposed by Weibull. The exponent, n, in Weibull's flaw distribution formula decreases, as it should with decreasing strength and ductility in limited selections of material under closely similar test conditions such as those referred to at the University of North Carolina. In various other groups of tests the results correspond to values of n ranging from 8 to 50. Large variations in the values of n appropriate to different tests and different material is not unexpected. The general trends of the results appear reasonable when one adopts the view that the system of flaws to which the statistical theory applies results from growth of flaws and development of fracture origins prior to the time of onset of unstable fast fracturing.

Although the statistical viewpoint as interpreted in this discussion is applicable to brittle fracturing, it is limited in its ability to describe the fracturing process in a mechanistic way. The statistical concept assumes, for example, that flawed regions act independently, whereas the joining up of fracture origins to form a crack of unstable size must be the essential basic event. Studies of the growth and joining of fracture origins as influenced by temperature, stress, and specimen size are, therefore, of special importance for a better understanding of fracturing metals at low temperatures.

Popularity Index - 0%

Jacobson, R.H., and Durelli, A.J., Development and Application of Brittle Material Method of Stress Analysis and Study of Brittle Failure Problems. (Final Report-Armour Research Foundation; Project No. 90-1081J, for Contract No. DA 11-022-ORD-454, Frankford Arsenal, Philadelphia, Pennsylvania, July 22, 1952). 94

Abstract

Brittle failure problems were studied and two approaches to explain adequately experimental data found in the literature were investigated. The first approach is based upon the statistical theories of failure. The literature pertaining to this subject was surveyed and appraisals of the papers studied are appended. An experiment was designed and conducted in which 252 beam specimens of 3 different span lengths were broken to

test a basic consequence of virtually all the statistical theories. The results obtained, however, seemed to indicate that the ultimate strength of these specimens is independent of their volume.

The second approach investigated was the particle theory, which assumes that brittle failures occur only when the average stress over a finite length, called the particle size, exceeds the ultimate strength. The theory was applied to results reported for the cases of central circular holes and notches in plates under axial loads, and fair agreement was found.

In a second phase of the project, work was carried out on the further development of the brittle material method of stress analysis. A new laboratory was established for this purpose and the equipment and casting procedure used are described. Experiments were performed in which agar was added to the formula for brittle plaster-mortar in an attempt to improve the homogeneity of the mortar. However, no improvement was indicated. By reducing the proportions of water used to prepare the mortar, it was found that improved homogeneity was obtained for all but the lowest sixth of a casting. Another experiment showed that the time required for brittle material tests could be reduced by drying the plaster-mortar castings at 120° F.

Popularity Index - 0%

Kimball, Bradford F., On the Choice of Plotting Positions on Probability Paper. (Journal of the American Statistical Association, 55, pp. 545-560, 1960). 95

Abstract

This article is an attempt to throw more light on the problem of choosing plotting positions for the frequencies related to ordered sample values. The problem is particularly pertinent where special-scale graph paper is used such that a straight line indicates conformance of data to type of distribution assumed to apply. Such graph paper is often briefly referred to as "probability paper." The types of distributions here considered are the normal and the extreme-value distribution of Type I, with the accent on the extreme-value case.

Various methods of determining plotting positions have been put forward and there is confusion of thought in judging what plotting convention is optimum. An optimum criterion proposed by Chernoff and Lieberman has received wide attention. Blom in a recent book develops further criteria.

To clarify the problem the author has analyzed the purposes to be served in plotting data on probability paper. With a specific concept of the purpose to be served in mind, it becomes clearer to the investigator which plotting convention would be the best one to use.

ARMOUR RESEARCH FOUNDATION OF ILLINOIS INSTITUTE OF TECHNOLOGY

Popularity Index - 0%

Kremser, Heinz, The Strength of a Tension Member in Dependence of its Length. (The Building Technology (Die Bautechnik) 5, pp. 169-171, 1956.) 96

Popularity Index - 0%

Lewis, Charles F., Graphical Solutions to Some Statistical Distributions. (ASME Publication No. 60-PET-9, presented September, 1960.) 97

Abstract

A graphical technique is offered for fitting statistical data to several useful distribution forms. The normal distribution is, in general, the first to be tried. If, for some reason, the measurement cannot take on values less than zero, it will be well to try either the Weibull or Gumbel distribution, or both. The former has been found very useful in life studies, and in strength of materials. The Gumbel is useful in those applications where the extreme values - either maxima or minima - are of paramount interest. To some extent, the areas of usefulness of these last two will overlap.

In more advanced analysis of the data, such as the confidence limits to be placed upon the estimates made, it is necessary to have reasonable estimates of the distribution parameters. These can also be gotten from the original plot by using the methods outlined here.

It is hoped that the presentation of these simple techniques will help to focus attention on the underlying statistical nature of much engineering information, and to foster a wider interest in their use as engineering tools. Statistical methods can never substitute for good, sound engineering judgment, but such methods can add substantially to the information to be gained from a given set of data.

Popularity Index - 0%

Lieblein, Julius, On Moments of Order Statistics from the Weibull Distribution. (Annals of Mathematical Statistics, 26 (2), pp. 330-333, 1955). 98

Abstract

This note expresses the first two moments of the order statistics in samples from the Weibull distribution (sometimes referred to as the

"third" asymptotic distribution of extreme values) in terms of known (incomplete B and Γ) functions. A similar procedure is applied to the "second" asymptotic distribution of extreme values.

Popularity Index - 0%

Mandel, J., The Theory of Extreme Values. (ASTM Bulletin, TP-39, February, 1959). 99

Abstract

The subject of extreme values involves the great variety of situations in testing and specifications in which the properties of interest depend on the frequency and the severity of flaws in the material. It is characteristic of such situations that the quality of the material is limited, not by its average value, but rather by its weakest spot. Workers in a variety of fields, such as metals, textiles, glass, and others have recognized this state of affairs and have quite often, and independently of each other, developed the same basic theory for such situations. Lately, the subject has received attention from the mathematical statisticians. The name of E. J. Gumbel is particularly well known in this field.

Some of the basic concepts and results in the theory of extreme values are presented briefly.

Popularity Index - 0%

Owen, Donald B., Tables of Factors for One-Sided Tolerance Limits for a Normal Distribution. (Sandia Corporation Systems Analysis Department, Statistical Division, April, 1958). 100

Abstract

This monograph presents tables of factors for a one-sided tolerance limit computed from a sample drawn from a normal distribution. The tables originate from four sources, and the accuracy of the tables from these sources is compared. The factors are percentage points of the noncentral t-distribution, and as such can be used in designing certain acceptance sampling plans.

Popularity Index - 0%

Press, Harry, Meadows, May T., and Hadlock, Ivan, Estimates of Probability Distribution of Root-Mean-Square Gust Velocity of Atmospheric Turbulence from Operational Gust-Load Data by Random-Process Theory. (National Advisory Committee for Aeronautics, Technical Note 3362, 1955). 101

Abstract

Under the assumption that the operational gust or gust-load history of an airplane is a Gaussian random process with a single parameter, the root-mean-square value, relations are derived between the probability distribution of the root-mean-square acceleration and the associated number of peak accelerations above given values. These relations are then used in the analysis of available operational gust-load data in the form of peak counts to derive estimates of the probability distributions of root-mean-square acceleration. These probability distributions are then transformed on the basis of airplane-gust-response theory in order to derive the associated probability distribution of root-mean-square gust velocity. The application of these results to the calculation of load histories is also considered briefly.

Popularity Index - 0%

Salmassy, O.K., Schwope, A.D., and Duckworth, W.H., Statistical Significance of the Strength of Brittle Materials. (Ceramics Bulletin, 33, 8, August, 1954). 102

Abstract

The definition of the "strength" of brittle materials is discussed. It is proposed that structures made of brittle materials be designed, not on the basis of the mean strength obtained from test data, but upon a stress corresponding to a given probability of fracture, as derived from a statistical analysis of the test data. The choice of a probability of fracture and its corresponding design stress is left to the discretion of the designer; however, the stress corresponding to zero probability of fracture, the "zero strength", is indicated to be of particular significance.

Popularity Index - 0%

Schuette, E.H., The Prediction of Exceedances in Limit-Value Testing. (Proceedings Statistical Methods in Materials Research, Pennsylvania State University, 1956). 103

Abstract

In my first excursion into the unfamiliar field of order statistics, I showed that if life tests were conducted in groups of n specimens each, with only the lowest of the n test results being recorded, then the median of such "least-of-n" results would be a value that might be expected to be exceeded by a percentage of the parent population given by $1/2^{(1/n)} \times 100$. Moreover, if fatigue tests are run by this procedure rather than the somewhat random spacing of the tests once common to the art, there would result increases in both the useful significance of the curve obtained and the quality of the data (Reduced scatter).

This proposal has aroused quite a lot of interest, especially from industrial laboratories who usually find it impractical to conduct full-blown statistical investigations. However, it soon became apparent that an extension of the first work was in order, for two predominant reasons: first, it offered no evaluation of the confidence levels appropriate to the results obtained, and second, it provided a knowledge of only one exceedance value, with no indication as to how broadly the curves for other values would scatter from the position of this one curve.

Further study of the applicable probability functions showed the possibility of meeting these objections with complete mathematical rigor in the case of tests aimed at determining a single life value corresponding to a fixed set of test conditions. Extension to the evaluation of the S-N curve in fatigue requires some departure from complete rigor, but can also be done with what I would consider intuitively adequate accuracy. These extensions of the original development are the subject of this paper.

Popularity Index - 0%

Shand, E.B., Stress Behavior of Brittle Materials. (Ceramics Bulletin 38, p. 653, 1959). 104

Abstract

Use of brittle materials effectively as structural elements depends upon the understanding of their stress behavior and the proper interpretation of mechanical tests. Relative brittleness of materials determines largely whether they fail in cohesion (brittle fracture) or in shear (ductile failure). Stress relations are also involved; triaxial tension increases greatly the tendency towards brittle fracture. Flaws of an accidental nature produce variances of breaking stress in brittle fracture. Probability

of failure at various stress levels has a pronounced influence on usable technical strengths. Because of delayed fracture under conditions of brittle failure, the meaning of the term "fatigue" must be reconsidered. Standard impact tests (Charpy and Izod), while very useful for ductile materials, have little significance when applied to brittle materials.

Popularity Index - 0%

Sheppard, H.R., and Ginsburg, H., Should Statistical Methods Be Used to Prepare Materials Specifications. (ASTM Bulletin TP 41, February, 1959). 105

Abstract

This paper consists principally of an analysis of some of the problems related to the use of statistical methods in preparing materials specifications. For the purpose of this analysis a materials specification is defined as follows:

> A materials specification is a written document which specifies values for all the important properties of a material together with limits of variability and methods for determining these values.

Materials specifications are looked upon differently by producers and consumers. The materials producer is concerned with his ability to meet the specification and supply the materials competitively. The consumer relies on the specification to assist in procuring a satisfactory material at a reasonable cost.

Popularity Index - 0%

Sorensen, F.A., Estimation of the Proportion of a Population Lying above a Fixed Value of the Variate. (Ballistic Research Laboratories, Memorandum Report No. 935, Department of the Army Project No. 5B0306002, Ordnance Research and Development Project No. TB3-0007, October, 1955). 106

Abstract

An expression is obtained for the asymptotic variance of a certain estimate of the proportion of a population lying above a fixed value. For several populations, the asymptotic variance of this estimate is compared with that of the estimate obtained by counting the number of

observations, in a sample, lying above this fixed value. The relative efficiencies of the two estimates are presented.

Popularity Index - 0%

Steck, George P., A Uniqueness Property Not Enjoyed by the Normal Distribution. (The Annals of Mathematical Statistics, 29, 2, June, 1958). 107

Abstract

It is well known that if X and Y (or 1/X and 1/Y) are independently normally distributed with mean zero and variance σ^2, then X/Y has a Cauchy distribution. It is the purpose of this note to show that the converse statement is not true. That is, the fact that the ratio of two independent, identically distributed, random variables X and Y follows a Cauchy distribution is not sufficient to imply that X and Y (or 1/X and 1/Y) are normally distributed. This will be shown by exhibiting several counter-examples.

Popularity Index - 0%

Su, Hsuan-Loh, Statistical Approach to Structural Design. (Proceedings Institution of Civil Engineers, 13, p. 353, July, 1959). 108

Abstract

The physical side of many structural problems is now well explored. However, the conventional method of the structural design is still far from satisfactory, because the statistical side of structural problems, which is of no less importance than the physical side, has seldom been considered.

A design method based on the principles of probability and statistics is introduced in the Paper. Three examples on steelwork, reinforced concrete, and soil mechanics are included for illustration. It can be seen from the examples that the suggested method, being based on statistics, is more rational than the conventional approach, and the design based on the proposed method will be more economical.

The Paper is intended only to introduce some applications of the statistical technique, which has been employed in many other industries. Further applications as well as the consequent influence on structural engineering will be discussed in a separate Paper.

Popularity Index - 0%

Volkov, S. D., A Unified Statistical Theory of Strengths of Solid Bodies. Trans. No. MCL-507 of Zhurnal Tekhnicheskoy Fiziki 23: pp. 2025-2037, 1953; AD-258-814, June 29, 1961). 109

Abstract

The present work has as its aim the development of a unified theory of strength which can be used both in the mechanism of fracture and to derive a single set of conditions of strength which will fit all stress states. This communication examines various inadequate technical theories of strength as well as the possibility of applying statistical mechanics to create a more general theory.

Popularity Index - 0%

Weibull, Woloddi, New Methods for Computing Parameters of Complete or Truncated Distributions. (Flygtekniska Forsoksanstalten, The Aeronautical Research Institute of Sweden, FFA, Report 58, February, 1955). 110

Abstract

Two new types of distribution moments are introduced which may be used with advantage for computing the parameters of a large family of functions. The procedure is demonstrated on a particular distribution function which has been found by experience to fit various static and fatigue strength data with good fidelity. The methods are also applicable to truncated or censored distributions which may be required when dealing with distributions composed of more than one component or with fatigue tests stopped at some predetermined time before all the specimens have failed. Numerical examples are given.

Popularity Index - 0%

Wiesen, J.M., Mathematics of Reliability. (Sandia Corporation Reprint, SCR-157, Proceedings Sixth National Symposium on Reliability and Quality Control in Electronics, p. 110, January 11-13, 1960). 111

Abstract

This discussion of the mathematics of reliability is limited to the topics of probability, probability distributions and their characteristics, estimation, and tests of hypotheses. Applications to the exponential distribution are indicated.

Popularity Index - 0%

Yokobori, Takeo, Failure and Fracture of Metals from the Standpoint of the Stochastic Theory. (Journal of the Physical Society of Japan, 8, 1, pp. 104-106, February, 1953). 112

Abstract

The phenomena of failure and fracture of metals were treated as a Markoff process or chain. In the fundamental types of failure and fracture, the physical meanings of transition probabilities were interpreted and they were found to correspond to the nucleation rate or reaction rate. The following fundamental features were unifiedly interpreted: (1) the dependence of strength on stress velocity or deformation velocity and temperature, (2) the dependence of the time for creep fracture on stress and temperature, (3) many features in the endurance limit and the dependence of the number of repeated cycles for fatigue fracture on the stress range, (4) the size effect, (5) the fluctuation characteristics, (6) ductility transition phenomena.

FATIGUE

ARMOUR RESEARCH FOUNDATION OF ILLINOIS INSTITUTE OF TECHNOLOGY

Christensen, R.H., and Denke, P.H., Crack Strength and Crack Propagation Characteristics of High Strength Metals. (ASD-TR-61-207, January, 1962. Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio). 113

Abstract

The purpose of this program has been to obtain engineering data on the crack propagation and residual strength characteristics of structural materials suitable for use in aerospace systems. Results of a fracture testing program for high strength sheet metals are presented. More than 500 sheet stock panels ranging in width from one to 18 inches and in thickness from .020" to .100" were tested. These panels contained centrally located cracks which were generated principally by fatigue loading at various exposure times under a variety of environments. In general, the fatigue crack is shown to be a more severe stress raiser than any manufactured notch yet investigated. Fracture strengths of the cracked panels were determined for rupturing temperatures ranging from -340° F. to 2,500° F.

The experimental results were studied analytically. A semi-empirical expression for residual strength is derived. This expression is based on a modification of the formula given by Crichlow for the effective width of the plastic zone. An expression for the rate of crack propagation also is presented. The crack rate formula is based on the plastic zone concept, and accounts for the observed approach to infinite cracking rates as the crack length approaches critical. These formulas are shown to agree well with test results and are suitable for design applications.

A digital analysis of the elastic and plastic stress and strain distribution in the cracked plate was performed. The analytical method is discussed and results are presented.

Crichlow, W.J., McCulloch, A.J., Young, L., and Meloon, M.A. An Engineering Evaluation of Methods for the Prediction of Fatigue Life in Airframe Structures. Technical Report No. ASD-TR-61-434, prepared under Contract No. AF 33(616)-6574, by Lockheed-California Company, a Division of Lockheed Aircraft Corporation, Project No. 1367, Task No. 136710, Flight Dynamics Laboratory, Aeronautical Systems Division, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, March, 1962). 114

Abstract

The results of a research study are presented for the comparison and verification of methods of fatigue life prediction suitable for handling

the complex problems encountered in the design and operation of modern aircraft. A general introduction to the problems of airframe fatigue analysis is given from the overall viewpoint of a system of design, development testing, and interpretation of fleet service history to maintain a necessary comparative basis for relating a practical fatigue life prediction method to operational results. From a study of twenty proposed fatigue life prediction methods, ten of the procedures were chosen for evaluation numerically with a group of seventy-eight complex spectral test results representing approximately 266 individual specimens.

An experimental program generated constant amplitude axial load S-N type data on simple notched coupons of 7075-T6 aluminum alloy sheet for use in the analysis procedures. Ordered spectral fatigue test data from these same type coupons were utilized from another concurrent ASD fatigue research program. New magnetic tape controlled fatigue test machines were utilized to apply simple spectra of gust, maneuver, ground, composite spectra of flight gust, ground taxi, and ground-air-ground transitions and composite spectra of flight maneuver, ground taxi, and ground-air-ground transitions. A series of specimens of a complex joint were also fatigue tested to the same simple ordered gust and maneuver spectra, and to the composite spectra of flight gust, ground taxi, and ground-air-ground transition cycles, and to composite flight maneuver, ground taxi, and ground-air-ground transition cycles. These data were analyzed by the selected procedures to confirm or provide a possible means of improving the selected fatigue life prediction methods.

Danek, Jr., G.J., Smith, H.H., and Achter, M.R., High-Temperature Fatigue in Controlled Environments. (NRL Report No. 5666, U.S. Naval Research Laboratory, Washington, D.C., September 8, 1961). 115

Abstract

The effect of environment on the high-temperature fatigue properties of nickel, Type 316 stainless steel, and Inconel X was investigated by comparing the fatigue life in air to that in vacuum at 1500° F. Sheet-metal specimens of these materials were cycled in reverse bending at their resonant frequency by means of equipment developed to perform high-temperature fatigue tests in controlled environments. A major problem in the design of such equipment, the transmission of motion through a vacuum seal, was solved by the use of a magnetic coupling device. A servomechanism control system serves the purpose of maintaining the amplitude and the center of vibration of the specimen constant and provides a means of stopping the test when a sudden decrease in resonant frequency indicates that a fatigue crack is beginning to propagate.

The effect of environment on fatigue properties is similar for all three materials. At high strains fatigue lives are superior in vacuum; with decreasing strain the vacuum and air curves converge. These results can be explained by a mechanism previously proposed to interpret similar

findings in creep. This mechanism involves the simultaneous operation of two competing processes: the surface adsorption of gaseous impurities lowers the surface energy and facilitates crack propagation, while oxidation provides a strengthening tendency.

In an investigation of the effect of section size on the fatigue properties of nickel in air and in vacuum, specimens 0.060 inches thick and 0.118 inches thick were cycled at 5 cps. It was found that a rapid convergence of the vacuum and air fatigue curves resulted in a crossing to produce a reversal of the environmental effect for the thinner specimens. No reversal was observed for nickel tested in the thicker sections. In air, the lowest strain tests on nickel of thicker cross section showed increases in resonant frequencies as the tests progressed and oxidation stiffened the specimen. However, the resonant frequency always decreased in vacuum.

In an effort to determine the effect of frequency on the environmental fatigue behavior of nickel, specimens of the same thickness were cycled at 5 and 12 cps. No frequency effect was observed in vacuum and in air at high strains. At 5 cps., however, the lowest strain air specimen exhibited a higher fatigue life than the one cycled at 12 cps.

A metallographic comparison of a nickel air specimen interrupted before failure and a vacuum specimen tested at nominally the same strain shows that more cracks exist in the supposedly stronger air specimen than the one cycled in vacuum to failure. Evidently, oxide formation in the cracks has become sufficiently load bearing to prevent failure.

The results of this investigation suggest that the criterion for failure in a high-temperature fatigue test should be examined with some care when applying such results to the prediction of load-bearing capabilities of structures.

Deneff, G.V., Fatigue Prediction Study. (Technical Report No. WADD TR 61-153, January, 1962, under Contract No. AF 33(616)-6901, Project No. 1367, Task No. 14002, Flight Dynamics Laboratory, Aeronautical Systems Division, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio). 116

Abstract

Fatigue life prediction of complex structure is investigated from the standpoint of fundamental factors that influence the prediction; namely, stress, fatigue strength, and damage method. Stresses developed by a general stress analysis procedure are combined with appropriate fatigue strength data to estimate the fatigue strength of a structural joint. Factors influencing the joint fatigue strength under spectrum conditions are analyzed and a method of estimating this fatigue strength is presented. Damage methods utilizing several types of fatigue strength data are considered. The influence of geometric factors on the fatigue strength of basic material is also studied and presented in a normalized form.

Douglas Aircraft Company, Inc., Investigation of Thermal Effects on Structural Fatigue. (WADD Technical Report 60-410, Part II, August, 1961, Flight Dynamics Laboratory, Contract No. AF 33(616)-6571, Project No. 1367, Task No. 14025, Aeronautical Systems Division, Air Force Systems Command, United States Air Force, Wright-Patterson Air Force Base, Ohio). 117

Abstract

The investigation of structural fatigue at elevated temperatures is extended to include higher temperature materials and more complex specimens. Rene' 41 and HS-25 materials are studied at temperatures up to 1800° F. and PH 15-7Mo up to 800° F. Mach 8 hypersonic aircraft spectrum tests are performed with Rene' 41 specimens including corrugated sandwich structure. PH 15-7Mo box beam, sandwich, and coupon specimens are tested to Mach 3 spectrum loads and tubular specimens are subjected to biaxial fatigue loading. Individual variable studies are made with notched, unnotched, and welded coupons. Predictions of spectrum fatigue life are compared with tests, and significance of local strain is considered experimentally and through analysis.

Ford, D.G., Graff, D.G., and Payne, A.O., Some Statistical Aspects of Fatigue Life Variation. (Department of Supply, Australian Defence Scientific Service, Aeronautical Research Laboratories, Structures and Materials Technical Memorandum No. 105, July, 1961). 118

Abstract

Fatigue tests conducted at the Aeronautical Research Laboratories on Mustang wings under repeated loading and also under various types of loading sequence have provided over 200 fatigue test results. This relatively large amount of data has permitted an investigation into statistical aspects of fatigue life variation. Data from other investigations, mainly on small specimens, have been included in the analysis, and the main topics are summarized below.

Freudenthal, Alfred M., Fatigue Sensitivity and Reliability of Mechanical Systems, Especially Aircraft Structures. (WADD Technical Report 61-53, July, 1961). 119

The increasing complexity of structural action and operation conditions of modern aircraft and space structures and the rising demand for reliable estimates of the expected operational life of the designed structure as a function of its anticipated mission, which reflects the realization that such structures must be designed for finite life, puts the designer into the frustrating position of having to choose between the conventional engineering design approach based on "safety factors", and the purely statistical reliability approach based on "mean time to failure", knowing that neither approach is really applicable in the design of large, fatigue-sensitive structures.

The present report attemps to develop an integrated design procedure for structures that have to be designed for a combination of "ultimate load" and "fatigue life" failure criteria, based on a quantitative measure of "fatigue sensitivity". The introduction of this measure permits not only a rational classification of structures in terms of their design fatigue sensitivity, but also their reclassification whenever changes in their operational missions produce significant changes in fatigue sensitivity.

Freudenthal, A.M., and Shinozuka, M., Structural Safety under Conditions of Ultimate Load Failure and Fatigue. (Columbia University, October, 1961, Directorate of Materials and Processes, Contract No. AF 33(616)-7042, Project No. 7351, Aeronautical Systems Division, Air Force Systems Command, United States Air Force, Wright-Patterson Air Force Base, Ohio). 120

Abstract

The purpose of this investigation is to analyze the concept of the safety of structures subject to operational loads that cause fatigue damage as well as to occasional excessive overloads that might produce ultimate load failure.

In Part I the relation between probability of failure and the reliability or the safety factor is discussed. Diagrams have been computed under the assumptions that the statistical variations of load and carrying capacity are expressed either by log-normal or by extremal distributions. The safety of multiple load-path structures, the probability of failure of simple structures under combined (primary and secondary) loads are also considered and the use of separate load factors for dead and live load is related to the concept of a single safety factor.

Part II deals mainly with the statistical properties of fatigue life distributions. Assuming a statistical-mechanical model for the fatigue mechanism, a new distribution of fatigue lives is derived. The concept of stress-interaction established in previous experimental research is used to reproduce the survivorship functions under random loading from the known survivorship functions associated with constant stress amplitude fatigue.

In Part III the risks of ultimate load and fatigue failures are combined and the reliability of aluminum specimens (AA 2024 A1) under both operational loads and occasional excessive overloads is investigated considering the interrelation with the risk-functions. The procedure is illustrated by a numerical example in which the truncated part of an exponential load spectrum is applied as operational (fatigue) loading while the rest of the spectrum produces the overloads.

Gatts, R. R., Application of a Cumulative Damage Concept to Fatigue. (Transactions ASME, Journal of Basic Engineering, pp. 529-540, December, 1961). 121

Abstract

A general concept of the accumulation of damage is described. This concept is combined with a particular hypothesis for the accumulation of fatigue damage. Initial and failure conditions are established for use with the equation and the solution for constant stress amplitude is discussed. Simple algebraic expressions are developed in terms of the nominal stresses and cycles commonly associated with machine design and stress analysis. These expressions are compared with data from rotating bending tests of steel specimens and found to be in good agreement. Nondimensional co-ordinates are used to provide a composite plot of S-N data from a wide range of steels.

Glassman, Larry H., and McEvily, Jr., Arthur J., Effects of Constituent Particles on the Notch-Sensitivity and Fatigue-Crack-Propagation Characteristics of Aluminum-Zinc-Magnesium Alloys. (National Aeronautics and Space Administration, Technical Note D-928, April, 1962). 122

Abstract

Sheet specimens of two aluminum-zinc-magnesium alloys, 7075-T6 and X7275-T6, were tested to determine the relative sensitivity to sharp notches under static loading conditions and to determine relative resistance to fatigue crack propagation. These alloys differ chiefly with respect to the number and size of constituent particles, the level being considerably lower in the X7275 alloy. Evidence is presented which indicates that reduction in particle size and number can increase somewhat the ductility of unnotched specimens without impairing the static strength, but the material with the greater constituent-particle content was found to be more resistant to fatigue crack propagation. For both materials the sensitivity to sharp notches under static loading conditions was about the same. A discussion and interpretation of the results are given.

Goode, Henry P., and Kao, John H.K., An Adaptation of the MIL-STD-105B Plans to Reliability and Life Testing Applications. (Transactions of the Fifteenth Annual Convention of the American Society for Quality Control, pp. 245-251, 1961). 123

Abstract

This paper presents a procedure, together with tables of necessary conversion ratios, for applying the MIL-STD-105B sampling-inspection plans to reliability and life-testing applications. The method assumes the Weibull distribution (including the exponential distribution) as a statistical model for item lifelength. Inspection of sample items is by attributes with life testing truncated at the end of some specified time, t. Lot quality is evaluated in terms of mean item life, μ , Both t and μ are measured from some reference time, γ.

Good, H. P., and Kao, J.H.K., (Cornell University), Sampling Procedures and Tables for Life and Reliability Testing Based on the Weibull Distribution (Mean Life Criterion). (Office of the Assistant Secretary of Defense, September 30, 1961,. TR-3). 124

Abstract

This technical report presents a proposed acceptance-sampling procedure together with tables of sampling plans for life and reliability testing when the underlying life distribution of items is of the Weibull form.

Hudson, C. Michael, and Hardrath, Herbert F., Effects of Changing Stress Amplitude on the Rate of Fatigue-Crack Propagation in Two Aluminum Alloys. (Technical Note D-960, National Aeronautics and Space Administration, September, 1961). 125

Abstract

A series of fatigue tests with specimens subjected to constant-amplitude and two-step axial loads were conducted on 12-inch-wide sheet specimens of 2024-T3 and 7075-T6 aluminum alloy to study the effects of a change in stress level on fatigue-crack propagation. Comparison of the results of the tests in which the specimens were tested at first a high and then a low stress level with those of the constant-stress-amplitude tests indicated that crack propagation was generally delayed after the transition to the lower stress level. In the tests in which the specimens were tested at first a low and then a high stress level, crack propagation continued at the expected rate after the change in stress levels.

Jenkins, P.C., and Morrison, J.D., An Investigation of the Crack-Propagation Resistance of High-Strength Alloys and Heat-Resistant Alloys. (Southern Research Institute, Bimonthly Progress Report No. 1, March 17, 1961, prepared under Bureau of Naval Weapons, Contract NOw 61-0392-d). 126

Abstract

In the program outlined in this report the crack-propagation characteristics of a number of heat-resistant alloys and high-strength alloys will be determined at room temperature and at elevated temperatures using fatigue-cracked specimens. A listing of these alloys, which fall into three general groups, is given. These groups are: refractory metals, super alloys, and some special "high-purity" steels. Details of the experimental procedures to be used for these alloys are presented.

An evaluation of the standard tensile properties and crack-propagation properties of aged A 286 alloy sheet, 0.040 inches thick, was made. It was found that the net fracture stress of fatigue-cracked specimens of this alloy is intermediate between the yield strength and ultimate strength at temperatures from 75° F. to about 1000°F. At 1500° F., the net fracture stress of the fatigue-cracked specimens was somewhat higher than the ultimate tensile strength.

Lehman, Jr., Eugene H., and Anderson, R.L., Estimation of the Scale Parameter in the Weibull Distribution Using Samples Censored by Time and by Number of Failures. (Sponsored by Office of Naval Research, Contract NONR-486(04)- Project NR-042-202, 1961). 127

Abstract

Researchers in many areas are interested in estimating the life span of individuals, be they human beings, animals, automobiles, or picture tubes. Each of these individuals is characterized by having a specific moment of birth, a specific moment of death, and a finite measurable life span. It is desirable to learn the distribution of the life span of these individuals.

These distributions vary from type to type, but past researchers have noticed empirically that the probability of death by time t (at least as great as β) often can be adequately approximated by the Weibull (1951) distribution:

$$F(t) = \begin{cases} 1 - \exp\left[-\frac{(t-\beta)^M}{\alpha}\right], & t \geq \beta \\ 0, & t < \beta \end{cases}$$

Liu, H.W., Fatigue Crack Propagation and Applied Stress Range-An Energy Approach. (ASME Paper No. 62-Met-2, 1962). 123

Abstract

Using the saturation of hysteresis energy absorption as a criterion for fatigue crack propagation, the rate of crack propagation in a thin and wide metal sheet under repeated axial loading is found to be proportional to the square of the applied stress range. The local stress and strain fields adjacent to the crack tip are employed to compute the energy density. The analytical results correlate very well with the experimental results on 2024-T3 aluminum alloy.

McEvily, Jr., Arthur J., and Machlin, E.S., The Effect of Repeated Stressing on the Behavior of Lithium Fluoride Crystals. (Technical Report R-91, National Aeronautics and Space Administration, 1961). 129

Abstract

Results of reversed-bend tests on LiF single crystals at 2 cpm are similar to those previously obtained at 1,800 cpm. indicating that speed effects are relatively unimportant. Reversed-torsion tests yield additional evidence that vacancy formation is not a primary cause of fatigue failure. Since LiF does not readily cross slip, the absence of fatigue failures lends further support to the theory that cross slip is necessary in order to obtain usual fatigue behavior. The results demonstrate that dislocation pileups do not lead to failure in LiF, and that plastic deformation in the course of reversed cycling will relax an initially applied mean load. Etch-pit studies yield visual evidence of the growth of slipbands during cycling.

Neuls, G.S., Maier, H.G., Lerwick, T.R., Robb, E.A., and Webster, I.J., Optimum Fatigue Spectra. (Technical Report No. ASD-TR-61-235, April, 1962, Flight Dynamics Laboratory, Aeronautical Systems Division, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, Project No. 1367, Task. No. 14025, Prepared under Contract No. AF 33(616)-6576,. by Douglas Aircraft Company, Inc., Long Beach, California). 130

Abstract

Information in this report is directed toward establishing an environmental load criteria for aircraft. Those subjects reviewed are

arranged in fundamental parameter form and describe gusts, maneuvers, landing, and taxi. That part of the environment which pertains to the individual aircraft type are examined to determine the compatibility with mission analysis and recommended operating practice. All information reported is documented with statistical data derived from airplanes in service.

In the process of determining fundamental parameters, some interesting discoveries were made with respect to gusts and taxi loads. A power spectral definition of gusts was derived that is analogous to the discrete gust but accounts for the size of the airplane with respect to a scale of turbulence. The results of this analysis define a common turbulence spectrum that satisfies all sizes of aircraft from a B-52 to a U-2 airplane. The intensity and amount of turbulence have been investigated from sea level to 75,000 feet.

A classification procedure for taxi environmental data was determined which utilizes a mean power spectrum, expressive of average runway harmonic content, scaled by a roughness intensity factor subject to a probability distribution. A measure of runway roughness, σ^2, sensitive to roughness intensity as actually felt by the airplane was developed and a probability distribution for the σ^2 was estimated. The mean spectrum and the σ^2 distribution were used in a statistical analysis of taxi loads for two types of transport airplane, which yielded results comparable with available experimental data. The technique of this analysis is outlined to provide a general means of statistically determining the taxi response of any given aircraft.

Paris, Paul C., Crack Propagation Caused by Fluctuating Loads. 131
(ASME - Paper No. 62-Met-3, 1962).

Abstract

The role of the crack tip stress-intensity factor concept in analyzing the rate of crack propagation under cyclic loading is discussed. Data are given to support the validity of use of the stress intensity factors as the controlling load variable in analyzing crack extension rates. The results are discussed with reference to life computations in structural applications, the possibilities for expansion of the theory to other than problems symmetric with respect to the crack, and possible approaches to the random or sequential loading areas.

Poppleton, E.D., On the Prediction of Fatigue Life under Random Loading. (University of Toronto, UTIA Report No. 82, AFOSR 2258, February, 1962). 132

Abstract

A review is given of some current methods of estimating fatigue damage and a new damage equation is derived based on the work of Corten and Dolan, and Torbe. This equation is applied to the case of a stationary Gaussian stress history and a discussion is given of the parameters appearing in the resulting equation for the fatigue life.

Raithby, K. D., A Comparison of Predicted and Achieved Fatigue Lives of Aircraft Structures. (Paper presented at A.G. A.R.D./I.C.A.F. Symposium on Fatigue, Paris, May, 1961, and reproduced for Official Use, July, 1961. Royal Aircraft Establishment, Technical Note No. Structures 301). 133

Abstract

This paper briefly outlines the methods currently adopted in the U.K. for the estimation of fatigue life of aircraft structures under service conditions. An assessment of the adequacy of the methods is made by comparing known cases of fatigue failures in service with the lives which would have been predicted for such cases. It is concluded that in the present state of knowledge on loading actions, fatigue performance, cumulative damage, and scatter in fatigue performance and load frequencies, the use of a simple approach with somewhat arbitrary safety factors is justified provided that fatigue tests have been made on a fully representative structure.

Smith, Jr., Preston W., and Malme, Charles I., Sonic Fatigue Life Determination by Siren Testing. (Technical Report No. ASD-TR-61-639, May, 1962, Flight Dynamics Laboratory, Aeronautical Systems Division, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, Project No. 1370, Task No. 137001, prepared under Contract No. AF 33(616)-7147, by Bolt Beranek and Newman, Inc.) 134

Abstract

Experimental and theoretical researches were made on the problem of predicting the fatigue life of a resonant structure exposed to jet noise by testing it with intense sound from a siren. One panel design of Alclad 2024 aluminum was tested to fatigue with constant-amplitude and variable amplitude siren sounds and with jet noise. A close correlation of all three results was found.

A comparison was also made of fatigue lifetimes of a resonant cantilever beam, of plain 2024 aluminum, measured with constant excitation amplitude (pure tone) and with random excitation. Random lifetimes were found to be shorter than predictions from constant-amplitude data.

Stulen, F.B., Cummings, H.N., and Schulte, W.C., Preventing Fatigue Failures. (Machine Design, July 6, 1961, The Penton Publishing Company, Cleveland, Ohio). 135

Abstract

Although fatigue failures have been investigated for more than 100 years, the basic mechanism of fatigue is still unknown. However, many methods have been formulated for the prevention of fatigue failures during expected service life of a part.

This series of articles discusses factors that affect fatigue strength. More important, it outlines methods which are helpful in the design of machine components and structural elements that must resist fatigue loading.

This first article discusses the factors which, in general, influence design for the greatest possible fatigue life. Subsequent articles will discuss geometric stress concentrations, effect of metallurgical and mechanical treatments on fatigue life, calculations for determining fatigue life, and effect of biaxial stresses on fatigue life.

Suski, H.M., Some Aspects of Go/No-Go Testing of Randomness of Continually Generated Binary Digits. (N.R.L. Report No. 5730, Security Systems and Avigation Branch, Electronics Division, U.S. Naval Research Laboratory, Washington, D.C., March 1, 1962). 136

Abstract

Pseudorandom numbers can be obtained statically, i.e., from a table of random numbers, or they may be generated continually (dynamically). Static cases have been investigated; e.g., tables of random digits often contain results of tests. The dynamic case, however, implies that tests for randomness be made continually. Go/no-go methods are attractive.

Problems associated with measuring randomness in the dynamic case of a generator continually producing binary digits are investigated. The mathematics of Bernoulli trials serves as the model against which the performance of the generator is compared. It is shown that there are a large number of ways in which a measuring system might be attempted.

Such systems are based on explicit functions (called measure functions) of p , the probability that a "one" is generated.

Since the digits can be grouped (a group consists of m digits), a binomial expansion $[p + (1 - p)]^m$ can be written for each value of m. Any term or combination of terms of any expansion can serve as a measure group, the basis of a measure function.

A typical measuring problem involves the case where p is constant and has a value within specified tolerances. A go/no-go measurement indicates that p is within the specified tolerances. Means are provided for the setting of measure group-count tolerances; a count alone then provides the indication of an acceptable or nonacceptable value of p. The sample size is selected on the basis of the desired confidence limit or the upper bound of the error in measuring p.

Since there are many possible measure functions, some means is required for comparing the relative effectiveness of different functions. A useful method of comparison is available if measure function "acceptance" characteristics are plotted. An acceptance characteristic is a plot of the probability that the measure group digits occur within the determined group-count tolerances. The acceptance characteristic is plotted for the results obtained from a single application of a particular measure function. By requiring a sequence of applications of the same measure function and by introducing an acceptance decision criterion, the acceptance characteristic more nearly approaches the ideal.

Task Group, Subcommittee VI, of ASTM, The Weibull Distribution Function for Fatigue Life. (Materials Research and Standards, ASTM, 2, 5, pp. 405-411, May, 1962). 137

Abstract

In 1958 ASTM Committee E-9 on Fatigue prepared a Tentative Guide for Fatigue Testing and the Statistical Analysis of Fatigue Data, which was published as Special Technical Publication STP91-A. This guide presents detailed instructions for applying certain statistical methods to the analysis of fatigue test results of samples and provides a means for estimating the characteristics of the population from which the samples were taken. There has been a demand from the roller bearing industry for the inclusion of an additional section covering the use of the extreme-value distribution originally proposed for the analysis of fatigue data by W. Weibull. Since Fisher and Tippett are often credited with first showing that this distribution was one of three limiting types of the extreme-value distribution, it is sometimes referred to as "Fisher-Tippett Type III for smallest values." As pointed out by Freudenthal and Gumbel, this distribution has some theoretical basis, assuming that fatigue failures are examples of extreme values, that is, they are smallest-strength or weakest-link values. It has also been used by others in the analysis of life test data.

Despite its widespread use by the roller bearing industry, the Weibull distribution has not received universal acceptance; in fact, there is considerable controversy over some of the assumptions that have been made in applying this distribution function to the analysis of fatigue data. For these reasons this proposed section on the Weibull distribution function is published at the request of the officers of Committee E-9 with the hope that those who have had experience with its use may help resolve some of the controversial problems and assist in putting this method for handling fatigue and other life data on a sound theoretical basis before it is included in STP 91-A.

Valluri, S.R., A Theory of Cumulative Damage in Fatigue. 138
(Guggenheim Aeronautical Laboratory, California Institute of Technology, Pasadena, California, December, 1961, Contract No. AF 33(616)-6270, Project No. 7024, Task No. -70666, Aeronautical Research Laboratory, Office of Aerospace Research, United States Air Force, Wright-Patterson Air Force Base, Ohio).

Abstract

A theory of cumulative damage is presented which is quantitative and is capable of explaining the effect of stress magnitude and is sensitive to the order of application of stress. The theory is based on a model of fatigue obtained from the elasto-plastic theory of cracks and on concepts from the dislocation theory of metals. The fundamental idea involved in the theory is the estimation of the length of a dominant crack that is presumed to grow during progressive fatigue whether due to a single stress or multiple stress loading. By referring all damage to the growth of this crack, it is found possible to treat the cumulative damage as a logical extension of the engineering theory of fatigue without making any other arbitrary assumptions. Applications of the theory to multi-step loading, program type loading, sequential random loading, and completely random loading have been discussed in a quantitative manner. Aspects of extension of the theory to acoustic fatigue which will be presented in a subsequent report, and some implicit limitations of the theory are also briefly discussed. The basic information necessary for the quantitative application of the theory is a statistically well defined stress versus number of cycles curve of fatigue. If this information is given, most of the aspects of cumulative damage can be predicted quantitatively. Comparison of the predicted results with the statistically reliable test results indicate the correlation to be excellent, the difference between the predicted fatigue lives from the theory and experiment being well within ten percent.

Valluri, S.R., A Unified Engineering Theory of High Stress Level Fatigue. (Guggenheim Aeronautical Laboratory, California Institute of Technology, ARL - 181, December, 1961, Contract No. AF 33(616)-6270, Project No. 7024, Task No. 70666, Aeronautical Research Laboratory, Office of Aerospace Research, United States Air Force, Wright-Patterson Air Force Base, Ohio.) 139

Abstract

A unified engineering theory of high stress level fatigue is proposed which enables one to understand and predict the various aspects of fatigue from the same basic model. This model combines certain features of dislocation theory of metals with elasto-plastic analysis of the stress distribution near a crack, and permits an estimate of fatigue life to failure based upon estimates of the rate of crack propagation. The theory predicts the shape of the familiar stress versus number of cycles curve extending from one fourth of a cycle at the ultimate static tensile strength down to several million cycles and incorporates no additional assumptions in predicting cumulative damage during fatigue. In particular, the theory distinguishes the order of application of stresses in cumulative damage. The weighting factor frequently associated with high stress levels in cumulative damage is implied in the basic model itself. The theory also discusses the dependence of fatigue upon the several commonly observed variables, some quantitatively and some qualitatively, as well as residual static strength in fatigue and its dependence on material properties. The inherently statistical nature of the fatigue problem is emphasized and this is attributed to an internal stress existing at the level of the lattice structure. This stress is thought to be due primarily to the existence of a network of dislocations and the solute atoms of alloying elements.

Watson, G.S, and Leadbetter, M.R., Hazard Analysis. (Research sponsored by the Office of Naval Research under Contract No. Nonr-3423(00) with the Research Triangle Institute, August 28, 1961). 140

Abstract

The hazard or conditional failure rate $h(x) = f(x)/(1-F(x))$ of a life-distribution has the same role in reliability studies as the spectral density-function in stationary time series analysis. There are many situations where the most revealing analysis of the data is the non-parametric estimation of $h(x)$. This paper begins the study of this approach to reliability. Of the many estimators suggested here, the most useful seems to be

$$\tilde{h}_n(x)_m = \sum_{r=1}^{m} \frac{\delta_n(x-X_{r|n})}{n-r+1}$$

where $X_{1|n} \leq \ldots \leq X_{n|n}$ is an ordered random sample of which the first m are available, and where $\delta_n(z)$ is a positive function depending on n, with an integral of unity, that approaches a delta-function as $n \to \infty$.

Popularity Index-13.48%

Weibull, W., A Statistical Representation of Fatigue Failures in Solids. (Transactions of the Royal Institute of Technology, Stockholm, Sweden, UDC 539. 431, No. 27, 1949). 141

Abstract

Extension of Weibull's statistical theory of strength of materials to fatigue loadings.

Popularity Index-13.41%

Epstein, Benjamin, and Sobel, Milton, Life Testing. (Journal American Statistical Association 48, p. 486, 1963). 142

Abstract

In this paper we discuss statistical problems which arise when the observations become available in an ordered manner. Usually observations made on a random variable do not become available in this way. If n items are taken from a machine and measured for some characteristic such as diameter, it would be quite an anomaly and indeed a cause for concern if the first item taken from the machine had the smallest diameter; the second item, the second smallest diameter, etc. However, there do exist numerous practical situations, for example, life testing, fatigue testing, and other kinds of destructive test situations where the data do become available in this way. We test n items drawn at random from some population and the data become available in such a way that the smallest observation comes first, the second smallest second, . . . , and finally the largest observation last. Clearly we can, if we choose, discontinue experimentation after we have observed the first r failures in a life test.

Popularity Index - 10.64%

Freudenthal, A.M., The Statistical Aspect of Fatigue of Materials. 143
(Proceedings Royal Society, London, 187A, pp. 416-429, 1946).

Abstract

The phenomenon which is usually described as 'fatigue' of materials, but for which the term 'progressive failure' would be more adequate, is the expression, on a macroscopic scale, of the progressive destruction of the cohesive bonds as a result of the repetitive action of an external load. It has the typical features of a mass phenomenon; both the cohesive bonds and the load repetitions are collectives in a statistical sense (Mises 1931). By applying the fundamental rules of the theory of probability many of the experimentally established relations between the principal variables can be theoretically deduced from the purely formal assumption of the existence of a statistical distribution function of the separation-strength of cohesive bonds.

Popularity Index - 10.39%

Epstein B., and Sobel, M., Some Theorems Relevant to Life Testing from an Exponential Distribution. (Annals Mathematical Statistics, Vol. 25, pp. 373-381, 1954). 144

Abstract

In this paper we have given a number of results which are useful in making estimates of θ based on life test information from one or more sets of data, where the underlying probability law is the two-parameter exponential distribution (1). If (1) is the underlying p.d.f., then

$$\log \frac{1}{1 - P(x;\theta, A_j)} = \frac{x - A_j}{\theta} \qquad (44)$$

where $P(x;\theta, A_j) = \Pr\left\{X \leqq x;\theta, A_j\right\}$. Thus it is clear that cases 1, 2, and 3 are equivalent to assuming that the theoretical life distributions in the various sets S_j will plot either as parallel straight lines or as the same straight line on the semi-logarithmic scale suggested by (44). The results of this paper serve to give a procedure for estimating the slope (common slope) of the line (lines). A_j can be interpreted as the sensitivity limit at the appropriate stress level.

Popularity Index - 9.38%

Kao, John H.K., Weibull Distribution in Life-Testing of Electron Tubes. (Journal American Statistical Association, 51, 275, p. 514, 1956). 145

Abstract

The properties of the Weibull distribution are studied. The maximum likelihood estimates of the shape and scale parameters of this distribution for an ordered and truncated sample are found. A logarithmic transformation of the Weibull distribution function makes possible the least squares estimates of these same parameters. Both methods of estimating parameters assume the location parameter equal to zero. This is reasonable in the case of failure age data because the observations have non-negative values and the exposure to risk starts immediately with experimentation. Experience with several sets of failure age data consisting of a total of more than two thousand electron tubes fitted to Weibull distributions provides evidence for a common shape parameter. If the location and shape parameters are known, the maximum likelihood estimator of the scale parameter has statistically desirable properties; namely, sufficiency, unbiasedness, consistency, and efficiency. Furthermore, with the location and shape parameters known one may transform the failure age data to fit an exponential distribution and certain theories derived for the exponential case carry over immediately.

Popularity Index - 9.20%

Ransom, J.T., and Mehl, R.F., The Statistical Nature of the Endurance Limit. (Journal of Metals, 185, pp. 364-365, 1952). 146

Abstract

For many years the Metals Research Laboratory of Carnegie Institute of Technology has been concerned with the statistical nature of the engineering properties of steel from an experimental viewpoint, particularly those properties representing ductility. In the past three years new work has been directed toward evaluating the statistical nature of the endurance properties. It has been shown that both the fracture curve and the endurance limit in fatigue are markedly statistical in nature.

Two methods have been adopted in this study: (1) straightforward statistical studies of cycles to fracture of a number of specimens at each of a series of stress levels, and (2) a new abbreviated statistical method, known as "staircase testing."

Popularity Index - 8.54%

Freudenthal, A.M., and Gumbel, E.J., On the Statistical Interpretation of Fatigue Tests. (Proceedings of Royal Society, London, A., 216, pp. 309-332, 1953). 147

Abstract

Progressive damage under repeated load cycles which leads to spreading, visible fatigue cracks, and finally to fracture in both metals and non-metals is a highly structure-sensitive process, the large-scale manifestations of which depend primarily on happenings on the submicroscopic and microscopic scale. This produces a considerable scatter in the results of fatigue tests performed under assumedly identical conditions. Thus, if n specimens are subjected to a sequence of stress cycles of the same amplitude S, they break at varying numbers of cycles; these numbers N taken in decreasing order, and the frequencies of survival at each number, determine, for each stress level S, a characteristic cumulative frequency distribution $1(N)_S$, the 'survivorship function'.

By formulating the phenomenon of consecutive fatigue fractures of the weakest within a finite (large) set of specimens as a problem of extreme values, the statistical theory of extreme values can be applied to the interpretation of the observed frequencies of survival at any stress amplitude. If, in first approximation, it is assumed that the probability of survival reaches unity only for N = 0 (no 'sensitivity threshold' in N), the survivorship functions are reproduced by the 'third asymptotic probability function of smallest values', which is represented on extremal probability paper by a straight-line relation between a reduced statistical variate y and $\log_{10}N$. Methods are presented for the computation of the two parameters of the survivorship function $1(N)_S$ from a set of fatigue data. The fit between the computed theoretical straight lines and the test results is satisfactory for fatigue tests of copper, aluminium, and a high-strength structural aluminium alloy.

Popularity Index - 8.33%

Orowan, E., Theory of the Fatigue of Metals. (Proceedings of the Royal Society, London, 171A, 944, pp. 79-106, 1939). 148

Abstract

The present theory of fatigue is based upon the fact that plastic deformation is not homogeneous. The stress acting upon a plastic inhomogeneity that is embedded in elastic surroundings is a function of its plastic strain, diminishing with increasing strain. This fact, with the assumption that the plastic spot is subject to strain hardening of the usual kind, leads to the existence of safe and unsafe ranges. The derived dependence of the safe range upon the mean stress of the cycle is the same as that deduced

by McAdam from empirical data. The relation between the stress range and the number of cycles after which a crack is formed, as calculated from the theory, is in accord with the typical log S-log N curves given by experiments. Conclusions from the theory about fatigue endurance at elevated temperatures, about the correlation between fatigue endurance and strength, about mechanical hysteresis, etc., are confirmed by experience.

Popularity Index - 6.49%

Freudenthal, A.M., and Gumbel, E.J., Minimum Life in Fatigue. (Journal American Statistical Association, 49, pp. 575-597, September, 1954). .49

Abstract

The existence of an "incubation period" of fatigue, that is of a finite threshold number of cycles $N_{o,s}$ below which, at a given stress level, fatigue failure will not occur and at which the probability of survival is therefore equal to unity has been established for certain metals and stress amplitudes. This phenomenon has also been confirmed by fatigue studies on both hard and mild structural steel at stress levels near and below their static yield stress. Therefore a "sensitivity limit" in terms of cycles (minimum life) appears to be as real an aspect of fatigue as the sensitivity limit in terms of stress (endurance limit), the existence of which is quite generally recognized.

The present investigation is part of a research project on the basic aspects of fatigue, conducted at the Civil Engineering Research Laboratories of Columbia University in New York, and is supported by the Research Corporation, the Higgins Fund and, in part, by the Office of Ordnance Research.

Popularity Index - 6.38%

Mendenhall, William, A Bibliography on Life Testing and Related Topics. (Biometrika 45, p. 521, 1958). 15.

Abstract

The following bibliography covers papers concerned with statistical theory and methods applicable to the study of the life characteristics of some biological or physical body.

Popularity Index - 6.25%

Freudenthal A.M., and Gumbel, E.J., Physical and Statistical Aspects of Fatigue. (Advanced Applied Mechanics, N.Y., 4, pp. 117-168, 1956). 151

Popularity Indes - 5.75%

Epremian E., and Mehl, R.F., Investigation of Statistical Nature of Fatigue Properties. (Technical Note 2719, National Advisory Committee for Aeronautics, June, 1952). 152

Abstract

A thorough review of the literature indicated the need for research on the statistical nature of the fatigue of metals. While much effort has been directed toward the effect of numerous variables on the average fatigue properties, the statistical variation of the mean properties and its causes have been virtually neglected. An extensive experimental program was undertaken to study this subject and to determine and evaluate the fundamental factors which influence this behavior.

The statistics of the fatigue-fracture curves and endurance limits were determined for a variety of materials and, by analysis of these experimental results, the effects of some metallurgical factors on the statistical nature of fatigue properties were shown. It was discovered that inclusions play a dominant role in this behavior and that other factors such as composition and microstructure are of secondary importance.

In addition, a number of other aspects of the problem were studied, namely, the dependence of statistical variations in fatigue life on stress level in the fracture range, the statistics of the location of crack initiation, the size effect and the understressing effect from a statistical viewpoint, and the form of the S-N diagram and the method of plotting it. For the most part, the experimental work was done in the pneumatic vibratory fatigue test machine which is more suitable than the usual R.R. Moore fatigue machine for these investigations.

Popularity Index - 5.56%

Epstein, Benjamin, Life Test Acceptance Sampling Plans when the Underlying Distribution of Life is Exponential. (Proceedings Sixth National Symposium on Reliability and Quality Control in Electronics, pp. 353-360, 1960). 153

Abstract

In this paper we suggest some life test acceptance plans which could, if suitably elaborated, play a role analogous to that of MIL STD 105A for attributes sampling. The main point of the paper is that, either implicitly or explicitly, life test acceptance sampling plans should take into account a priori knowledge. In particular, if life test sampling plans are to be used in situations where there is a flow of lots, then accumulated information on the quality level of past lots should be a factor in determining whether to use a normal, reduced, or tightened plan. The rules governing the operation of the plans have some arbitrary features, which may need modification in specific instances. It should also be emphasized that in this paper we make the assumption that the underlying distribution of life is exponential.

Popularity Index - 5.56%

Kao, John H.K., A Summary of Some New Techniques on Failure Analysis. (Proceedings of the Sixth National Symposium on Reliability and Quality Control in Electronics, pp. 190-201, 1960). 154

Abstract

A statistical model for lifelength of components or systems called Weibull distribution is used as the basis of these techniques. Life quality in the statistical sense is defined before the analysis are made. Methods of parameter estimation including a graphical approach are given. The construction of confidence band on the distribution function using published tables is indicated with examples. Designs of life tests for the purpose of obtaining trade-off curves are sketched. A more complicated statistical model leading to better fit to empirical data is discussed.

Popularity Index - 5.56%

Zelen, M., and Dannemiller, Mary C., Are Life Testing Procedures Robust? (Proceedings of the Sixth National Symposium on Reliability and Quality Control in Electronics, pp. 185-189, 1960). 155

Abstract

Almost all the statistical procedures in current use for evaluating the reliability of components or equipments rest on the assumption that the failure times follow the exponential distribution. In practical situations one rarely has enough data to determine whether failure times are actually exponential. This paper studies the behavior of several statistical life testing procedures based on the exponential failure law if the true failure law is Weibull distribution. It is found that these statistical techniques, which

are widely used, are very sensitive to departures from initial assumptions. Applying these techniques to life test data when the exponential failure law is not satisfied may result in substantially increasing the probability of accepting components or equipments having poor reliability.

Popularity Index - 4.69%

Lieblein, J., and Zelen, M., Statistical Investigation of the Fatigue Life of Deep-Groove Ball Bearings. (Journal of Research of the National Bureau of Standards, 57, 5, pp. 273-316, November, 1956). 156

Abstract

Fatigue is an important factor in determining the service life of ball bearings. Bearing manufacturers are therefore constantly engaged in fatigue-testing operations in order to obtain information relating fatigue life to load and other factors. Several of the larger manufacturers have recently pooled their test data in a cooperative effort to set up uniform and standardized ball-bearing application formulas, which would benefit the many users of antifriction bearings. These data were compiled by the American Standards Association, which subsequently requested that the National Bureau of Standards perform the necessary analyses. This paper summarizes the principal results of the analyses undertaken by the Bureau, and describes the statistical procedures used in the investigation.

Popularity Index - 4.65%

Kao, John H.K., A Graphical Estimation of Mixed Weibull Parameters in Life-Testing of Electron Tubes. (Technometrics, 1, 4, p. 389, November, 1959). 157

Abstract

It is widely recognized that electron tube failures may be classified into two types: sudden and delayed. A mixture of two Weibull distributions, each representing one type of tube failure, is proposed, and a simple graphical method for estimating the parameters of the mixed Weibull distribution described.

The use of Weibull distribution (1) in characterizing the lifetime of electron tubes was first studied by the author some years ago. Some of the results were given in (2, 3, 4, 5). The present paper includes a refinement in the mathematical model as follows. Instead of a single distribution, a mixture of two Weibull distributions each representing a type of tube failure is postulated. The concept of two failure types, sudden and

delayed, concurs with the field experience on tube failure. This new model proposed here, allows even more flexibility in data fitting with very little additional complexity over the single-population model used earlier. A simple graphical method of estimating the parameters of the mixed Weibull distribution on a special graph paper is illustrated by using actual life-testing data gathered by a small-scaled life-test of some 800 6AQ5A's conducted at Cornell University under a Signal Corps contract. The construction of a statistical confidence band on the theoretical failure distribution utilizing the incomplete beta function table is also described.

Popularity Index - 4.65%

Sobel, M., and Tischendorf, J.A., Acceptance Sampling with New Life Test Objectives. (Proceedings of the Fifth National Symposium on Reliability and Quality Control in Electronics, pp. 108-118, 1959). 158

Abstract

As an alternative to the use of MIL-STD-105-A, AQL tables, etc., for life testing applications, a life test sampling plan is developed which accepts a lot at the end of a given test time only if a specified mean life objectives is established at a prescribed confidence level, i.e., it guarantees protection to the consumer. Tables give the minimum number of units to be put on test for various acceptance numbers, for various confidence levels, and for various ratios of test time to the specified mean life objective. These tables are based on the assumptions of an exponential distribution of life and an infinite lot size (binomial distribution theory); the results are then compared with the results obtained by the less conservative assumption of a finite lot size where hypergeometric distribution theory replaces binomial distribution theory. The "producer's risk", in terms of mean life, which is associated with these plans is illustrated by a table computed for one of the confidence levels treated.

Popularity Index - 4.65%

Zelen, Marvin, Factorial Experiments in Life Testing. (Technometrics, 1, 3, p. 269, August, 1959). 159

Abstract

This paper discusses procedures for analyzing factorial experiments, where the experiment deals with the life testing of components or equipment. These procedures assume an underlying general distribution of "times-to-failure," of which the exponential, Weibull, and extreme value distributions are special cases. Statistical tests and confidence procedures

are outlined, and an example illustrating the procedure for life-test results of glass capacitors is included. Small sample approximations, which are adequate for practical applications, are given for the proposed procedures. This is shown empirically by generating thousands of life-test experiments on an electronic computer. An empirical sampling investigation is given of the robustness of the proposed procedures. From the sampling results, it is concluded that these techniques are sensitive (non-robust) to departures from the original assumptions on the probability distribution of failure-times. An investigation is also given of a transformation which appears to give robust results. These same techniques carry over exactly to the situation where one is analyzing an array of variance estimates from an underlying normal population.

Popularity Index - 4.26%

Mendenhall, William, and Hader, R.J., Estimation of Parameters of Mixed Exponentially Distributed Failure Time Distributions from Censored Life Test Data. (Biometrika, 45, Parts 3 and 4, December, 1958). 160

Abstract

Statistical methods in life testing analysis have been developed in the past primarily for the case of a single failure population. In this paper a failure population which can be divided into subpopulations, each representing a different type or cause of failure, is considered. Estimates of the population parameters are obtained in the case where the subpopulations are exponentially distributed and sampling is censored at a predetermined test termination time.

Popularity Index - 3.90%

Epstein, Benjamin (Department of Mathematics, Wayne University), Life Test Estimation Procedures. (Technical Report No. 2, July 15, 1954, Research done under Contract DA-20-018-ORD-13272 with the Office of Ordnance Research of the U.S. Army). 161

Abstract

In this paper we bring together in one place procedures for finding point and interval estimates of the mean of an exponential distribution of life, where the data upon which the estimates are based can arise in various ways. A statistic which we call "total life" underlies all of the estimates treated in this paper. Several numerical illustrations are given.

Popularity Index - 3.19%

Baker, T.C., and Preston, F.W., Fatigue of Glass under Static Loads. (Journal of Applied Physics, 17, 3, p. 170, 1946). 162

Abstract

Static loading tests were run on glass and porcelain rods 7/32 inch in diameter for times ranging in duration from 0.01 second to 24 hours, by using specially designed apparatus. It was found that glass can support for 0.01 second about 3 times the stress that would break it in 24 hours. The effects are generally the same for all glassy materials. Porcelain showed the effect somewhat less than glass. It appeared that adsorbed moisture and gases reduced the strength.

Popularity Index - 2.78%

Epstein, Benjamin, Tests for the Validity of the Assumption that the Underlying Distribution of Life is Exponential. (Technometrics, 2, 1, p. 83, February 1960). 163

Abstract

It is frequently useful to test, on the basis of life test data, whether or not one is justified in assuming that the underlying distribution of life is exponential. This paper, which appears in two parts, describes a number of graphical and analytical procedures for testing this assumption. Part I of the paper contains descriptions of the mathematical and graphical procedures. Part II contains several worked examples.

Popularity Index - 2.78%

Mendenhall, W., and Lehman, Jr., E.H., An Approximation to the Negative Moments of the Positive Binomial Useful in Life Testing. (Technometrics, 2, 2, p. 234, May, 1960). 164

Abstract

The purpose of this paper is to obtain the mean and variance of the maximum likelihood estimator of the scale parameter of a Weibull distribution where the sample is censored at a fixed time. It will be shown that these moments are functions of the negative moments of the positive binomial distribution. A simple approximation is obtained for the negative moments of the positive binomial, thus giving an approximate expression for the mean and variance of the estimator.

Popularity Index - 2.78%

Whaley, Richard E., and Kurzhals, Peter R., Fatigue-Crack Propagation in Aluminum-Alloy Tension Panels. (Technical Note D-543, National Aeronautics and Space Administration, November, 1960). 165

Abstract

Results are presented of a series of fatigue tests to study crack propagation and the resulting stress distributions in tension panels. The panels were all of the same general design, and configurations varied mainly in the relative amount of cross-sectional area in the skin, stiffeners, and flanges. The panels were constructed of 2024-T3 and 7075-T6 aluminum alloys. It was found that the average rate of crack growth was slower in panels made of 2024-T3 aluminum alloy than in panels made of 7075-T6 aluminum alloy. All cracks initiated in the skin, and the slowest crack growth was measured in configurations where the highest percentage of cross-sectional area was in the stiffeners.

Strain-gage surveys were made to determine the redistribution of stress as the crack grew across the panels. As a crack approached a given point in the skin, the stress at that point increased rapidly. The stress in the stiffeners also increased as the crack approached the stiffeners. During the propagation of the crack the stress was not distributed uniformly in the remaining area.

Popularity Index - 2.33%

Johnson, Leonard G., The Statistical Treatment of Fatigue Experiments. (Research Laboratories, General Motors Corporation, G.M.R.-202, April, 1959). 166

Abstract

In the last decade one of the most convenient methods of treating fatigue test data is that which makes use of the so-called Weibull Distribution. W. Weibull, of Sweden, was the first to extensively use this particular method, wherein straight line graphs are used to represent cumulative percentages of failures by means of appropriate coordinate scales. This method is especially convenient for engineering purposes, because a clear graphic picture of the fatigue life distribution makes it so much easier to convey the statistical decisions with which the test engineer is concerned.

Popularity Index - 2.33%

Signorelli, R.A., Johnston, J.R., and Weeton, J.W., Thermal-Stress Fatigue Cracking of Turbine Buckets Operated at 1700° F. in a Turbojet Engine with Frequent Starts and Stops. (Technical Note D-125, National Aeronautics and Space Administration, October, 1959). 167

Abstract

Five high-strength nickel-base bucket materials were tested in a J47 turbojet engine at 1700° F. The investigation was conducted to study the effects of advanced-temperature operation on thermal-stress fatigue resistance of several of the newer turbine-bucket alloys. Inadvertently, the buckets were subjected to frequent starts and stops during the test. The bucket materials used in the test were SEL-1, B and B, Inconel 713, cast Udimet 500, and wrought Udimet 500.

Thermal-stress fatigue cracking on the leading edge of the buckets was observed in all alloy groups after short operating times. Cracks occurred in some groups after only 10 starts (6 1/2 hours at rated speed) and had occurred in all groups after 28 starts (30 hours). At the conclusion of the test (49 starts and 70 hours), 60 to 90 percent of the buckets of each alloy had developed cracks. Thermal-stress fatigue cracks did not progress rapidly by stress-rupture to cause fracture of buckets. Only one bucket fractured during the test; a thermal-stress fatigue crack progressed by mechanical fatigue to fracture. This bucket was run with cracks for 31 hours before fracture. Other buckets ran with cracks for as long as 63 hours without fracture.

Popularity Index - 2.25%

Peterson, R.E., Approximate Statistical Method for Fatigue Data. (ASTM Bulletin No. 156, pp. 50-52, January, 1949; Discussion: ASTM Bulletin No. 158, p. 62, May, 1949). 168

Abstract

Very little use has been made of statistical methods for analysis of fatigue data, because (a) the number of test values seldom exceeds 20, and (b) these values are spread over various stress levels. If we had, say, 90 test values, 30 at each of three stress levels, statistical methods might be applied, but this has not been done and probably will not be done very often in the future.

This being the case, is there any hope of analysis of 20 to 30 values obtained in the usual way? It is thought that perhaps the following approximate method will give somewhat better information than the measured width of the usual shaded scatter band.

Popularity Index - 1.56%

Bore, C.L., The Presentation of Fatigue Data for Fatigue Life Calculations. (Journal Royal Aeronautical Society, 60, pp. 331-346, 1956). 169

Abstract

A simple and convenient "endurance chart" for the presentation of basic fatigue data is described, where static failure is regarded as simply fatigue failure in one cycle of loading.

This chart shows the effects of mean stress, residual stress and pre-tension, and displays several interesting features of fatigue data. It is easily constructed directly from fatigue test results, and is very well suited to the calculation of stress concentration effects, including "plastic relief" effects.

With the aid of such charts the relative fatigue strengths and structural efficiencies of different materials may be readily compared, and it is clearly shown that in certain circumstances a "high-strength" alloy may in fact have considerably less fatigue strength than a "medium-strength" alloy at a given life, or conversely a lower life at a given stress level.

It is demonstrated that the fatigue life of a component subjected to combined mean stress and alternating stress may be found only with a knowledge of the complete fatigue characteristics of the material (such as are presented in the endurance chart); and that attempts to estimate fatigue life from spot-value comparisons, such as the fatigue strength at an arbitrary given endurance, can be dangerously inaccurate. A chart of the form described thus forms a valuable step towards the accurate calculation of fatigue life.

The method is illustrated by the provision of endurance charts for 14S-T(L.65), 75S-T, and D.T.D. 683; and with experimental results for notched components of L.65 and D.T.D. 683.

An example illustrates the application of the chart to the calculation of the fatigue life for the case of two independent systems of loading acting on a pressure cabin with circular window cut-outs.

Popularity Index - 1.56%

Freudenthal, A.M., and Gumbel, E.J., Distribution Functions for the Prediction of Fatigue Life and Fatigue Strength. (London Conference on Fatigue of Metals, Session 3, Paper 5, 1956). 170

Abstract

The two most serious problems facing the designer confronted with the results of tests specifying the fatigue life at constant stress amplitudes or the fatigue strength for a certain number of stress cycles of a material subjected to a specific set of fatigue testing conditions are:

1. The correlation of testing and service conditions.
2. The prediction of the range of variation of fatigue life and fatigue strength associated with a certain level of statistical significance.

Because of the wide scatter of results characteristic of fatigue tests, the second problem is more serious in fatigue testing than in mechanical testing in general.

Since the designer is necessarily concerned with fatigue lives or strength values associated with an extremely small probability of not being attached (10^{-3}) to (10^{-6}), while the practically feasible number of tests can usually only provide the respective figures in the probability range of between 10^{-1} and 10^{-2}, the problem of extrapolation of actual test results to design figures is of considerable practical importance. The introduction of a 'safety factor' evades the difficulty of such extrapolation by transferring the problem to a different plane, that of engineering common sense which, while providing a figure for the safety factor, does not provide a criterion to judge its adequacy. It can be shown that the establishment of such a criterion requires the consideration of the reliability of the very extrapolation which the safety factor attemps to eliminate (Freudenthal 1954).

The basis of an effective extrapolation of test results is the presentation of these results by a distribution function which is physically germane to the phenomenon the statistical variation of which it describes. Curve-fitting without regard to physical significance does not provide a basis for extrapolation over probabilities of several orders of magnitude, since no effective discrimination is possible between the various distribution functions on the basis of fitting curves to test results extending only over a relatively narrow range about the mean or median.

Distribution functions are, therefore, introduced and discussed which, because of their physical association with the fatigue phenomenon, can be used for extrapolation of test results to the design range, and the interrelation is established between the distributions of fatigue life N and of fatigue strength S and the trend of the S-N diagram.

Popularity Index - 1.56%

McClintock, F.A., The Growth of Fatigue Cracks under Plastic Torsion. (Institute of Mechanical Engineers, London, pp. 538-542, 1956). 171

Abstract

Recent investigations (for example, Dolan 1954; McClintock 1955; Thomson 1956) have shown that fatigue cracks form at a small fraction of the total life of a specimen subjected to repeated stress. Hence, knowledge of the fatigue life of structures and machines depends to a large extent upon an understanding of the rate of growth of fatigue cracks. In addition, the requirements for light weight in many structures and machines, along with their complexity, mean that early models of a product may well contain elements which will be subject to fatigue failure. The question of how often such machines must be inspected in order to prevent catastrophic failures is primarily one of determining how quickly the most sensitive unobserved crack will grow to complete failure. Finally, a knowledge of the rate of growth of fatigue cracks is necessary when crack-like defects are initially present in the material or arise in fabrication.

A major obstacle to understanding the rate of growth of fatigue cracks is the absence of a theoretical solution for the distributions of stress and strain in the neighbourhood of a sharp notch in an elastic-plastic material. The distribution of stress and strain around a sharp crack in an elastic material was found over forty years ago (Inglis 1913). To be sure, engineering structures of practical interest generally contain stresses below the elastic limit. But once a crack develops, application of the theory of elasticity as outlined by Inglis leads to the prediction of infinite stresses. Even the correction of that theory by considering the boundary conditions applied to the deformed, rather than the original boundary (Bowie 1955) results only in a reduction of the theoretical stresses at the root of a sharp notch to a value equal to Young's modulus. Thus there must be a small region in which plastic flow is taking place, at least in structures large enough so that the region of high stress includes several grains. The mathematical difficulties involved in studying the mixed elastic-plastic problem have prevented any exact solutions. Up to the present time, investigators have resorted to approximations in order to get equations simple enough to handle. Uzhik (1950, 1956) has assumed that the strain distribution in the plastic region is similar to that before plastic flow began, an assumption counter to the experimental results of Hardrath and Ohman (1951). Head (1953) has developed an idealized model in which the plastic zone is assumed to be a constant width as the crack progresses.

Another approach to the problem is to choose a specimen shape and loading system such that the distributions of stress and strain, even in the plastic region around cracks, can be computed theoretically. Such a case is given by long bars subjected to torsion, where the combined membrane and sand-hill analogies are available (Prandtl 1903; Nadai 1923) and the general method of obtaining the strain distribution has been given by Mandel (1946). It is the object of this paper to report theoretical and experimental studies of the growth of cracks in bars subjected to fully plastic cycles of torsion. If the results of such investigations are favourable, extension to the more complicated elastic-plastic case is in order.

Popularity Index - 1.47%

McClintock, F.A., The Statistical Theory of Size and Shape Effects in Fatigue. (ASME Paper No. 55, 1955). 172

Abstract

Fatigue specimens are considered in which the stress amplitude is constant with respect to time but falls off parabolically along the length of the specimen from the point of maximum stress. From assumptions regarding the local variability in the strength of the material, equations are derived relating the scatter in cycles to failure to the scatter in position of failure. The effect of specimen size is determined for these two types of scatter, as well as for the average life. It is found that the shape of the distribution function does not affect seriously the relation between scatter in cycles to failure and scatter in position of failure. The size effect, however, is markedly influenced by the shape of the distribution function. A modification is suggested to make the results applicable to tests to determine the endurance limit, where the stress amplitude is a variable.

Popularity Index - 1.30%

Spaulding, E.H., Design for Fatigue. (SAE Transactions 1954). 173

Abstract

Steps in fatigue design of aircraft lower wing surfaces, as presented here, are:

1. Selecting a structure that permits easy fatigue-crack detection. X-ray inspection of blind areas is suggested.
2. Setting a design quality standard. This is the important stress-concentration factor K_t, which is shown to have a lower practical limit.
3. Choosing a design gross area stress rather than net section stress to give the desired life. The gross area stress is also a better basis than the 1.0 g operating stress level for comparing fatigue life in similar aircraft.
4. Step testing to check design quality. This preferred method of fatigue testing is discussed here.

Popularity Index - 1.22%

Epremian, E., and Mehl, R.F., The Statistical Behavior of Fatigue Properties and the Influence of Metallurgical Factors. 174

(ASTM Special Technical Publication No. 137, p. 25, 1953).

Abstract

As a result of this study and research, the following conclusions are made:

1. Both the fatigue life and endurance limit are subject to marked variability, and therefore these quantities cannot be stated as single values, but must be represented statistically.
2. In view of the statistical nature of fatigue properties, the design engineer must, in choosing a factor of safety, recognize the fact that some failures can occur prematurely or even at stresses below the normally determined endurance limit. An approximate method of predicting such premature failures in the absence of statistical data is provided for the case of steels.
3. The S-N diagram does not follow the simple curve which is usually drawn, but has a point of inflection and bends toward the stress axis at shorter life.
4. Analysis of the measurements of the location of fatigue crack initiation provided further evidence of the inhomogeneous nature of the steel and its influence on the statistical behavior in fatigue.
5. The dispersion in fatigue life in rotating and vibrating tests increases with decrease in stress in the fracture range. In torsional fatigue, however, the dispersion is independent of the level of the stress. A theoretical interpretation of these observations is proposed.
6. The variability in fatigue properties depends upon the metal and is influenced by metallurgical factors.
7. From the available data, the statistical variation in the fatigue life of non-ferrous metals (for example, copper and aluminum) appears to be less than that for iron or steels, probably because the former materials have fewer inclusions and inhomogeneities.
8. From data in the literature cold drawing appreciably increases the variability in fatigue life of a steel. Apparently imperfections have a greater effect in the cold-worked metal, and perhaps the working operation itself increases the nonuniformity of the material.
9. Of the many factors which can influence the statistical behavior of fatigue properties, inclusions are the most important. Two steels of the same chemical composition, (that is, SAE 4340) but with widely different inclusion ratings have correspondingly different variabilities.
10. The effect of differences in composition and microstructure of iron and steels on the degree of dispersion is overshadowed by the inclusion contents of the materials. A steel of given composition can have greater or less variability than iron, depending upon whether its inclusion rating is relatively high or low.
11. At a given inclusion rating, the material with higher ductility yields less scatter in the endurance limit, but the dispersion in fatigue life is essentially the same.

ARMOUR RESEARCH FOUNDATION OF ILLINOIS INSTITUTE OF TECHNOLOGY

Popularity Index - 1.10%

Gurney, C., and Pearson, S., Fatigue of Mineral Glass under Static and Cyclic Loading. (Proceedings Royal Society, London, A, 192, 537, 1948). 175

Abstract

Round soda-glass rods were broken in four-point bending. In one series of experiments, the load was increased at a constant rate until fracture occurred, and in another series, the times to fracture under a range of constant loads were determined. Tests in each series were made under three different test conditions - non-rotating, rotating at 14 r.p.m., and rotating at 10,000 r.p.m.

It is concluded from the experiments that glass does not fatigue under cyclic loading appreciably faster than it does under static loading. This was in accord with expectations, if the static fatigue of glass is due to the spread of cracks rather than to deterioration of the inherent strength of flawless material.

As fracture of glass under static conditions is not preceded by flow and work hardening as it is for metals, the difference in fatigue behaviour of glass and metals is an indirect indication that the fatigue of metals is associated with flow and work hardening, and thus agrees with more direct evidence on the nature of fatigue in metals.

Popularity Index - 0%

Bailey, R.W., Usefulness and Role of Repeated Strain Testing as an Aid to Engineering Design and Practice. (Proceedings Institute of Mechanical Engineers, 131, pp. 131-349, 1953). 176

Abstract

The phenomenon of what has become known as fatigue in metals, first attracted the attention of early engineers by the disconcerting fracture of engineering and machinery parts under the action of repeated and cyclic stresses of lower magnitude than might have been expected from the known static properties of metals, and by design. Much more is now known of the phenomenon, but, by and large, the fact of cracking and fracture is still the most significant occurrence disclosing that the phenomenon has been present, and that other fractures may follow, or that a crack having begun may be expected to continue, and its progress even accelerated because of the stress concentration influence of the crack, but cracking is the primary and visual evidence and consequence of fatigue, and the common criterion.

Important use may be made of this criterion as an aid to design in judging whether design stresses and strains can be regarded as safe, and the purpose of this paper is to draw attention to the value of repeated strain

tests as an important aid to design and to the determination of effective material properties where plastic strain may enter, and greatly modify by reduction, computed stresses according to elastic theory.

Popularity Index - 0%

Basquin, O.H., The Exponential Law of Endurance Tests. (Proceedings of the American Society Test Material, 10, pp. 625-630, 1910). 177

Popularity Index - 0%

Birnbaum, Z.W., and Saunders, S.C., A Statistical Model for Life-Length of Materials. (Journal of American Statistics Association 53, pp. 151-160, 1958). 178

Abstract

A statistical model for life-lengths of structures under dynamic loading is derived. The model makes it possible to express the probability distribution of life-lengths in terms of the load given as a function of time and of deterioration occurring in time independently of loading. The special case of a constant load (or of periodic loading with constant amplitude) leads to gamma distributions for life lengths.

Popularity Index - 0%

Dieter, G.E., and Mehl, R.F., (Carnegie Institute of Technology) Investigation of the Statistical Nature of the Fatigue of Metals. (Technical Note 3019, National Advisory Committee for Aeronautics, Washington, September, 1953). 179

Abstract

It has been widely accepted recently that statistical methods of investigation are necessary for meaningful work in studies on the fatigue of metals. The statistical nature of the endurance limit was first demonstrated in the Metals Research Laboratory, Carnegie Institute of Technology, less than 5 years ago. A subsequent study showed that for steel the chief metallurgical variable influencing the statistical nature was the nonmetallic inclusion count.

The present investigation utilized the statistical methods developed in previous research to study the scatter found in aluminum alloys and

the effect of the morphology of the carbide phase on the scatter in a eutectoid steel. The scatter in fatigue life for 24S and 75S aluminum was found to be comparable with that reported previously for steel. As was found in previous investigations, the scatter increased with decreasing stress level. A pronounced effect of microstructure was found when a coarse pearlitic structure was compared with a coarse spheroidized structure in the same steel with the same tensile strength. The scatter from the pearlitic structure was significantly less than that in the spheroidized, this result being attributed to the stress concentration produced by the sharp carbide lamellae.

Popularity Index - 0%

Dieter, G.E., Horne, G.T., and Mehl, R.F., Statistical Study of Overstressing in Steel. (Technical Note 3211, National Advisory Committee for Aeronautics, 1954). 130

Abstract

The effect of overstressing on the fatigue properties of SAE 4340 steel has been studied statistically. The effect of microstructure on the susceptibility to reduction in fatigue life due to cycles of overstress was investigated. When tested at equivalent percent stress, the quenched and spheroidized structure was found to be more susceptible to fatigue damage.

The effect of overstress on the endurance-limit statistics was studied for the quenched and spheroidized structure. Enough specimens were tested to determine the endurance-limit statistics of damage specimens by the probit method. The decrease in the mean endurance limit due to cycles of overstressing was much greater than would be expected from nonstatistical investigations which are reported in the literature. The effect is interpreted as support for the belief that the bulk of the fatigue damage takes place before the first 30 percent of the total fatigue life.

Popularity Index - 0%

Epstein, Benjamin, Exponential Distribution and Its Role in Life Testing. (Industrial Quality Control, p. 4, December, 1958). 131

Abstract

Many current results in life testing are based on the assumption that the life X is described by a probability density function $f(x;\theta)$ of the form

$$f(x;\theta) = \frac{1}{\theta} \exp\left[-x/\theta\right] \qquad x>0, \quad \theta>0 \qquad (1)$$

In (1), x is life measured in appropriate units (for example, hours) and

$$E(X) = \int_0^\infty x f(x;\theta)\,dx = \int_0^\infty \frac{x}{\theta} \exp\left[-x/\theta\right] dx = \theta \qquad (2)$$

is the mean life expressed in appropriate units. There is evidence that the lives of electron tubes or the time intervals between successive breakdowns of electronic systems are, to a first approximation, random variables having the density (1).

Popularity Index - 0%

Epstein, Benjamin, Operating Characteristic Curves and Other Features of Truncated Life Tests with Replacement. (Technical Report No. 5, May 15, 1953, Prepared Under Contract Nonr-451(00), (NR-042-017) for Office of Naval Research. Department of Mathematics, Wayne University, Detroit, Michigan). 182

Abstract

In (1) we considered the properties of truncated life tests under the assumption that the underlying life distribution is exponential. The purpose of this report is to furnish some tables and graphs for the replacement case when items which fail are replaced at once by new items.

The underlying probability density function of life is assumed throughout to be

(1) $\quad f(x;\theta) = \frac{1}{\theta} e^{-x/\theta}, \quad x > 0, \ \theta > 0.$

The test is started with n items drawn at random from (1). Any item which fails is replaced at once by a new item drawn from (1). The experiment is truncated at time $T = \min(X_{r_o, n}, T_o)$, where $X_{r_o, n}$ is the time (measured from the beginning of the experiment) when the r_o'th failure occurs and T_o is a truncation time beyond which the experiment is not permitted to run.

Popularity Index - 0%

Ferguson, Robert L., A Further Investigation of the Effect of Surface Finish on Fatigue Properties at Elevated Temperatures. (Technical Note 3142, National Advisory Committee for Aeronautics, March, 1954). 183

Abstract

An investigation was conducted to evaluate the effects of surface roughness on fatigue properties of low-carbon N-155 alloy with a grain size of A.S.T.M. 6 and of S-816 alloy with a grain size of A.S.T.M. 6 to 7. Fatigue studies were conducted at 80°, 1200°, 1350°, and 1500° F. In addition, an investigation of the effect of surface abrasion upon the nature, direction, magnitude, and depth of residual stresses and of the effect of time and temperature upon the relief of these stresses was conducted.

The stress concentration effect of the surface roughnesses investigated was found to lower the fatigue strengths of both N-155 and S-816 as much as 10 percent at the temperatures and times considered. This observation was made after the surface compressive stresses induced by roughening, which tend to increase fatigue strength, were reduced by annealing.

A study of strips roughened by abrasion showed that the abraded surface contains compressive stresses at right angles to the scratches and tensile stresses parallel to the scratches. These residual surface stresses may remain during fatigue cycling at low temperatures and when of sufficient magnitude act to appreciably increase fatigue strength. At elevated temperatures, however, these beneficial stresses were relieved during cyclic stressing and only the detrimental stress concentration effects produced by abrasion remained and reduced fatigue strength.

Popularity Index - 0%

Frost, N.E., and Phillips, C.E., Studies in the Formation and Propagation of Cracks in Fatigue Specimens. (London Conference on Fatigue of Metals, Session 6, Paper 2, 1956). 134

Abstract

This paper describes past and current work at the Mechanical Engineering Research Laboratory, East Kilbride (M.E.R.L.). The problem of the stress raiser in a specimen subject to fatigue loading, whether under zero mean load or subject to superimposed mean loads, is one that has been studied intensively over the past years. Many hypotheses have been suggested to explain the difference between the theoretical geometrical factor K_t for the notch or stress raiser based on the theory of elasticity, and the fatigue strength reduction factor K_f obtained by experiment. K_f is either equal to or less than K_t depending on specimen size, material, and notch dimensions.

It is not intended to discuss in detail the various attempts made to find a relationship between K_t and K_f; many of these have been collected and reviewed by Dolan and Yen (1952). Two problems are of outstanding interest in the field of notched fatigue specimens. The first is the effect of size of test piece and the consequent difficulty of relating data from laboratory work to component performance. Many authors have found that, for

geometrically similar specimens, the larger the specimen the nearer K_f approaches K_t. The second problem is concerned with the fact that the fatigue strength reduction factor does not necessarily continuously increase with increase in notch sharpness. This last point has been thoroughly investigated up to the present only on round bar specimens (Frost 1955a; Mann 1953; Hyler and others 1954). Size effects have been investigated in both round bar and sheet specimens. Neither of these effects can be explained by plastic flow causing redistribution of the stresses around the notch and a consequent reduction in the calculated elastic stresses.

In order to obtain a better understanding of the above problems, work has been carried out at the M.E.R.L. along the following lines. A notched specimen that fails under the influence of fatigue loading will do so by the formation and subsequent propagation of a crack at the root of the notch; hence detailed knowledge of the conditions for initiation and propagation of such cracks is of the utmost importance. Metallurgical examinations have been made of the material at notch roots, and the formation of cracks which do not propagate has been observed in both round bar and plate specimens. Tests on plate and sheet specimens are in progress to measure rates of propagation of fatigue cracks and also to obtain the relative periods occupied by the initiation and propagation. Other tests, currently being carried out, relate to the strength of cracked specimens. These are in two categories: (1) round bar specimens are precracked in bending and then tested either in rotating bending or in direct stress with or without a mean load; (2) plate and round bar specimens containing a notch are tested until a crack appears, the notch then being machined away and the cracked specimens tested in the normal manner. The following sections of the paper describe the above work in detail.

Popularity Index - 0%

Glathart, J.L., and Preston, F.W., The Fatigue Modulus of Glass. (Journal of Applied Physics, 17, pp. 189-195, March, 1956). 185

Abstract

The decline in the breaking strength of glass with an increase in the length of time it is under stress has been noted by various experimenters. Based on the experimental results of T.C. Baker, an empirical relationship is obtained which indicates that the reciprocal of the breaking stress is a linear function of the logarithm of the duration of the stress. Certain implications of this relationship are discussed.

Popularity Index - 0%

Hult, J.A.H., Fatigue Crack Propagation in Torsion. (Journal of the Mechanics and Physics of Solids, 6, pp. 47-52, 1957). 186

Abstract

The redistribution of stress and strain in front of a growing crack in a twisted bar is derived, assuming the material to be ideally plastic. The result is used in connexion with a simple fracture criterion to determine the initial rate of growth of a fatigue crack. Experiments with torsion members are reported.

Popularity Index - 0%

Kennedy, A.J., Problems of Combined Creep and Fatigue Design. (Engineer, 204, 5305, p. 444 September 27, 1957). 187

Abstract

Although the actual conditions which occur in practice in high temperature machines and in special structures, such as aircraft, may be very complex in their nature, technological development has been based almost entirely on standard tests under fairly fixed conditions. As a result, the fatigue or the creep properties of materials are examined in isolation, usually at constant stress and temperature. The more fundamental aspects of these processes have also been studied in isolation, and consequently few pointers have been provided for the development of a more realistic testing policy. The difficulties which arise in dealing with the generalized problem of the simultaneous operation of deformation and fatigue processes, under varying conditions, are so great that the established test methods, and the approximations they involve, may well be thought adequate for the purpose. The greater the demands that are made on materials, however, the less adequate such approximations will become. From an economic point of view, the present system is already too expensive to be capable, in its present form, of a general expansion, even if this were desirable on scientific grounds. The fact is that some changes must come in the future and exactly what form they will take depends upon the results of research. As yet these results are too insubstantial to offer more than an outline of what will be involved. It is useful, however, to take stock of the present situation and this article therefore reviews the evidence relating to interaction between the two processes of deformation and fatigue, particular attention being given to the case where the deformation occurs by creep.

Popularity Index - 0%

Kihara, Hiroshi, and Masubuchi, Koichi, Effect of Residual Stress on Brittle Fracture. (Welding Research Supplement, pp. 1595s-1685s, April, 1959). 188

Abstract

The authors made an experimental investigation of the effect of residual welding stress on brittle fracture. For this purpose, the specimens having sharp transverse notch in the region of high-tensile residual stress were pulled by testing machine under various temperatures. Through the experiment it was found that residual welding stress having no effect on the ductile fracture of welded structure may play an essential role in the case of brittle fracture. The complete fracture of a welded joint may be produced by merely applying low stress in a static manner when such unfavorable conditions as the use of materials of low notch toughness, existence of sharp notch, and high-tensile residual stress are accumulated. The above-mentioned fracture at low stress level is one of the realization of brittle fracture which occurred in the actual damages.

The effect of preloading at high temperature on the behavior of a joint was also investigated and it was found that the preloading produces favorable effect on the fracture strength at low temperature.

In addition, the authors' personal opinions on the application of stress-relieving heat treatment and nondestructive testing for the prevention of brittle fracture are also presented.

Popularity Index - 0%

Orowan, E., The Fatigue of Glass Under Stress. (Nature, pp. 341-343, September 9, 1944). 189

Abstract

My purpose here is to show that the decrease of the breaking stress with increasing duration of loading can be explained on the basis of the Griffith theory without ad hoc assumptions, and that in this way the ratio of the breaking stresses for very short and very long duration of loading can be calculated, in reasonable agreement with experiments. It will be seen that, in the absence of other causes of fatigue, this explanation demands the existence of a safe stress roughly equal to a third of the short-time strength. It suggests that, on extending the duration of loading beyond the range so far investigated, the logarithmic strength - time curve would bend away from the inclined straight line and go over asymptotically into a horizontal line, corresponding to constant strength for very long times of breaking.

Popularity Index - 0%

Peterson, R.E., Fatigue Tests of Small Specimens with Particular Reference to Size Effect. (American Society of Steel Treatment, 13, pp. 1041-1056, 1930). 190

Abstract

This paper gives data concerning a small fatigue testing machine weighing ten pounds and taking a test specimen fifty thousandths of an inch in diameter at the critical section. Fatigue tests on this small machine are compared with similar tests on larger machines. It is shown that for ordinary steels no appreciable size effect occurs up to two inch diameter. For cast iron the results obtained with small specimens are erratic and considerably lower than for specimens of ordinary size. Some observations are also made on heating effect in specimens of different diameters.

Popularity Index - 0%

Peterson, R.E., Review of the Fatigue of Materials Field. (Applied Mechanics Reviews, 5, 1, January, 1952). 191

Abstract

Fatigue failures continue to be one of the problems involved in design and operation of machinery and transport vehicles. In the operation of Liberty ships in three recent years, about 100 propellers were lost at sea due to fatigue failures of the screwshaft. There have been only two catastrophic aircraft failures due to structural fatigue failure, but the minor fatigue failures of "nuisance" category, which are corrected in maintenance operations and reported to C.A.A., have been occurring at the rate of about 30 per month. Fatigue cracks appearing in railway axles require considerable inspection and maintenance programs. Fatigue fractures occur in various types of machinery, including gas turbines. Recently fatigue cracks have been discovered in the Boulder transmission lines. These lines have a right-of-way of 325 miles and have been in service 15 years.

Popularity Index - 0%

Poncelet, Eugene F., A Theory of Static Fatigue for Brittle Solids. (Transactions - American Society for Metals, 40, B, pp. 201-227, 1948). 192

Abstract

Static fatigue is measured as the time required for the failure to set in when the solid is subjected to a given stress.

This important and well-established fact cannot be reconciled with any of the classical theories of strength of brittle solids, which do not take the duration factor in consideration.

Popularity Index - 0%

Press, Harry, and Houbolt, John C., Some Applications of Generalized Harmonic Analysis to Gust Loads on Airplanes. (Journal of the Aerospace Sciences, 23, 1, pp. 17-26, January, 1955). 193

Abstract

A review is first made of the various aspects involved in the application of the techniques of generalized harmonic analysis to airplane dynamic behavior in rough air. These aspects include: the concept of a power spectrum for the compact characterization of a random disturbance in time, the use of the spectrum for calculating airplane response to gust disturbances, and the relation between the statistics of the time history and the power spectrum. A recently developed technique due to I. Tukey for the derivation of spectra estimates from time history data is also described.

The available information on the spectrum of atmospheric vertical velocity is summarized and a representative spectrum selected for use in the applications.

Some of the significant applications to gust load problems made to date at the NACA are then presented. These applications are intended to illustrate the effects of three important factors involved in the airplane response to gusts, namely, the center of gravity position, short period damping, and wing bending flexibility. In each case, experimental verification of the calculated results is given.

Popularity Index - 0%

Pugsley, A.G., The Behaviour of Structures under Repeated Loads. (Journal of the Royal Aeronautical Society, 51, p. 715, September, 1947). 194

Abstract

In recent years some types of aircraft have shown signs of structural trouble due to repeated loading and exploratory thought has

therefore been given to the general problems arising. There are two main aspects to be considered: the nature and magnitude of the loads repeatedly occurring in flight and the behaviour and strength of aircraft structures under such loads. In this country a good deal of attention has already been given to the first side of the question, mainly by V-g recorder work, but also by some strain gauge investigations, but the other side of the matter - the resistance of aircraft structures to repeated loading - has so far received less attention. Direct experiments have not in this country gone much beyond exploratory work on a series of Typhoon tailplanes, described by Oaks and Townshend.

In these circumstances it has seemed desirable to approach this second aspect of the matter from the standpoint of tests on materials and on structural elements incorporating stress concentrations typical of aircraft structural practice. This paper outlines a picture built up in this way, of the behaviour to be expected of elementary structures under repeated loading.

Popularity Index - 0%

Ransom, J. T., A Guide to Statistical Methods for Use in Fatigue Testing. (Stockholm Conference, pp. 229-234, 1954). 195

Abstract

Describes a manual which is being prepared by a Task Force in the ASTM Committee E-9 on Fatigue. The purpose of this manual is to provide an outline of step-by-step procedures for using statistical methods in fatigue testing. The manual is intended for testing engineers without statistical training. We hope that the availability of such simplified outlines will permit everyone to make more use of these methods. This in turn will lead to the collection of information which in the future will permit more precise recommendations to be made.

The manual will consist of three principal sections. In the first we clarify those basic statistical concepts which will be useful in fatigue testing. In the second section we present statistical procedures which have been used to study fatigue strength, that is, the maximum stress which can be tolerated for a given life. In the third section we outline procedures for analyzing fatigue life data, that is, data obtained at a given stress or groups of data obtained at several stresses.

Popularity Index - 0%

Ransom, J. T., The Staircase Method for Estimating the Fatigue Limit. (Proceedings Statistical Methods in Materials Research, Pennsylvania State University, June, 1956). 196

ARMOUR RESEARCH FOUNDATION OF ILLINOIS INSTITUTE OF TECHNOLOGY

Abstract

The staircase method has been found most useful for estimating the median fatigue limit of various materials or the median fatigue strength of nonferrous materials at any given number of load cycles. It has several inherent advantages over other methods for this purpose. When one is primarily interested in the median value, for a given desired precision of the estimate the staircase method requires approximately 30 percent fewer specimens than does the Probit method. It requires fewer specimens because the staircase method automatically concentrates the testing about stress levels near the median fatigue limit and fewer specimens are wasted on the tails of the distribution. Furthermore, as will be shown, the mathematical analysis to arrive at the estimated values is quite simple and rapid. The method has one inherent disadvantage in that it requires waiting for the result of one test before proceeding to the next test.

Popularity Index - 0%

Schuette, E.H., A Critical Look at Fatigue Equations. (Product Engineering, pp. 150-151, June, 1952). 197

Abstract

Because it is often impractical to test a material for an infinite number of cycles, investigators have proposed numerous empirical methods of describing the stress-number of cycles or S/N relationship. The purpose of these methods is the extrapolation to infinity of limited test data.

Popularity Index - 0%

Shand, Errol B., Fracture Velocity and Fracture Energy of Glass in the Fatigue Range. (Journal of the American Ceramic Society, 44, 1, pp. 21-26, January, 1961). 198

Abstract

A method is developed for determining crack velocities from the stress-time curve of fracture. Velocities of glass broken in air and in vacuum converge at a value between 1 and 10 mm. per second. This convergence is considered to be the upper limit of the fatigue range. Fracture energy has been computed in terms of strain energy release rates. For glass broken in air under low stresses this energy is about equal to the surface energy of the glass, but when in vacuum it is fifteen times greater. At the upper limit of the fatigue range it is thirty times greater, whereas at the terminal velocity of fracture it is of the order of fifty times greater. It is concluded that surface energy must constitute only

a small part of the energy absorbed in the fracture process. This excess energy has a pronounced influence on the fracture process and on the measured strength of glass.

Popularity Index - 0%

Shanley, F. R., A Proposed Mechanism of Fatigue Failure. (Stockholm Conference, pp. 251-259, 1956). 199

Abstract

It has been shown that the proposed mechanism of fatigue offers a rational basis for explaining many well-known fatigue phenomena. The only direct disagreement is found with those fatigue theories in which crack initiation is attributed to a localized lowering of the strength of the material.

Popularity Index - 0%

Signorelli, Robert A., Johnston, James R., and Waters, William J., Thermal-Stress Fatigue Cracking of Turbine Buckets Operated at 1700° F. in a Turbojet Engine with Long Periods of Operation between Starts. (Technical Note D-272, National Aeronautics and Space Administration, February, 1960). 200

Abstract

Four high-strength nickel-base bucket materials were tested at 1700° F. in a J47 turbojet engine. The operating time between starts was increased compared with a previous investigation (TN D-125). The investigation was conducted to study the effect of increased operating time between starts on the thermal-stress fatigue resistance of the alloys tested. The bucket materials used in this test were Sel-1, B and B, forged Udimet 500, and Inconel 713.

Thermal-stress fatigue cracking occurred in some buckets of each alloy group early in the test and in 48 to 100 percent of the buckets of each alloy group at the conclusion of the test (after 33 starts and 357 hours at rated speed). Although thermal-fatigue cracking occurred early, only two buckets fractured (broke into two or more pieces) during the test. Increased operating time between starts permitted substantial increases in accumulated rated-speed operating time for all alloys before bucket cracking occurred. Compared with the previous investigation (TN D-125) increased operating time between starts decreased the number of starts to cause cracking of buckets for alloys B and B and forged Udimet 500, but not for alloys Sel-1 and Inconel 713. Increased operating time between starts also increased the number of buckets cracked for a given number of

starts for alloys Sel-1, B and B, and forged Udimet 500. The mode by which bucket cracks progressed to fracture was the same as described in TN D-125. The fractures occurred by mechanical-fatigue progression of thermal-stress fatigue cracks.

Popularity Index - 0%

Stromeyer, C. E., The Determination of Fatigue Limits under Alternating Stress Conditions. (Proceedings Royal Society, A 90, pp. 411-425, 1914). 201

Popularity Index - 0%

Stulen, Foster B., On the Statistical Nature of Fatigue. (ASTM Special Technical Publication No. 121, 1954). 202

Abstract

Usually conventional fatigue tests are not designed to evaluate the character and dispersion of the fatigue life and endurance limit of a material, and as a result little is known about these important characteristics of materials. Several methods are proposed in this paper for the determination of these characteristics, and the results of tests utilizing these techniques as well as methods of graphically representing the data are given.

The elementary theory of extreme values as related to the size effect is given in this paper. Explanations of the understressing effect and of the variation in notch sensitivity between different materials are proposed.

Tests have also been conducted which show that the material near the surfaces and edges of the specimens appears to have lower endurance limits than the material in the interior of the specimens. This is in agreement with observations recently made by several other investigators.

Popularity Index - 0%

Stulen, Foster B., Cummings, H.N., and Schulte, W.C., Statistical Aspects of Fatigue; Some Practical Aspects of Fatigue. (Proceedings Statistical Methods in Materials Research, Pennsylvania State University, 1956). 203

Abstract

In previous lectures of this seminar various statistical formulas and techniques have been discussed so that the research worker in material properties will have some basic knowledge of these powerful tools and techniques for the planning, execution, and interpretation of material investigations.

It has become more apparent to designers, engineers, and operators in recent years that the strengths and life expectancies of many machines and of some of the so-called "static" structures are not governed by the magnitudes of their critical steady stresses alone, but also by the magnitudes and cycles of the imposed vibratory or alternating stresses. Moreover, there is a wide "scatter" in these strengths and life expectancies. In the future, there will be increasing emphasis in the trend towards lighter machines and structures because of the rising costs of the raw materials, manufacture, and operation. This trend will, in turn, emphasize the need for greater precision in the knowledge of the service loads and environments as well as in the knowledge of the statistical fatigue behaviour of materials subjected to these loads and environments.

Popularity Index - 0%

Torrey, M. N., and Gohn, G. R., A Study of Statistical Treatments of Fatigue Data. (Proceedings American Society Test Materials, 59th Anniversary Meeting, 1956). 234

Abstract

This paper summarizes the results of reversed-bending fatigue tests on two lots of commercial Grade A (5 percent tin) phosphor bronze strip and presents the observed values (48 values for each deflection level) so that others may use them for further statistical analysis. The distributions of cycle life are fitted by logarithmic-normal, extreme value and log-log-normal distributions, showing that the type of distribution depends on the deflection (stress) value. The use of response curves is suggested.

Popularity Index - 0%

Tye, Walter, The Outlook on Airframe Fatigue. (Journal of the Royal Aeronautical Society, 59, pp. 339-348, May 1955. The Second Barnwell Memorial Lecture.) 235

Popularity Index -0%

Uzhik, G. F., Mechanical Aspect of Size Effect on Fatigue of Metals. (London Conference on Fatigue of Metals, Session 2, Paper 17, 1956. 206

Abstract

In numerous papers on the fatigue of metals published during the past twenty to thirty years, investigators, in choosing grooves on specimens of different sizes, confined themselves to only one geometrical similarity. Thus, the size effect was studied under conditions of simultaneous action of two factors: the discontinuity of the materal and the discontinuity of stressing. That is why it appears at present to be impossible to establish the extent to which the absolute sizes are connected with the discontinuity of the material itself. This research can be promoted only by further experiments under conditions which exclude violation of similarity in stressing. Then, along with the accumulation of experimental data on size effect connected with the discontinuity properties of the material alone, which change with size increase, it seems possible to estimate the degree of this discontinuity, for instance, with the help of the statistical theory of strength.

Within the last few years investigations have been carried out on the size effect in tension and in compression, that is under conditions when there was no possible influence of the stress gradient, and similarity of stressing in the surface layer was provided for.

As is known, no size effect has been discovered (Phillips and Heywood 1951; Hempel 1951; Massonet 1955).

These results, strikingly consistent with each other, indicate that the discontinuity of the material itself is not likely to decisively affect the fatigue strength under a size increase. The study of the size effect attains, therefore, still greater significance under the above examined conditions.

Interim results obtained by the author in the bending tests of specimens, which have ten times size variations (specimen diameter being 7.5 and 75 mm.) testify that under such conditions the size effect proves to be considerably smaller.

If these results are confirmed, then it will be possible to determine the fatigue limits in machine components of large dimensions by testing small-size specimens, provided there exists similarity of the stress state of their surface layers.

Popularity Index - 0%

W. Weibull, Basic Aspects of Fatigue. (Stockholm Colloquium on Fatigue, pp. 289-298, 1956). 207

Abstract

It is convenient to think of a specimen under repeated stresses as undergoing a progressive, accumulating damage. This concept has been applied to the total fatigue process with more or less success, in some cases leading to controversial opinions.

The purpose of this paper is to demonstrate that some of the difficulties may be eliminated, if due consideration is taken to the fact that the fatigue process consists of two stages of quite different nature: the crack initiation and the crack propagation, and if the concept of cumulative damage is applied, not to the total complex process, but to a single point of the specimen, during the first stage that point where the crack is suspected to start, and during the second stage an arbitrary point at the prospective path of the crack.

Popularity Index - 0%

Weibull, Waloddi, Statistical Evaluation of Data from Fatigue and Creep-Rupture Tests. Part I - Fundamental Concepts and General Methods. (WADC Technical Report 59-400, Part I, Materials Laboratory, Contract No. AF 61(514)-1208, Project No. 7360, Wright Air Development Center, Air Research and Development Command, United States Air Force, Wright-Patterson Air Force Base, Ohio, September, 1959). 208

Abstract

Fatigue tests are classified into three types with consideration to the appropriate method of evaluating the data. Fundamental statistical concepts, general methods, and useful tools are presented.

The possibilities of estimating distribution parameters have been examined. Starting from the concept of information available in a sample, various methods of estimating the parameters of location, scale, and shape are discussed, completed by a comparison of the efficiency of various estimates.

General principles of fitting curves to observations are outlined and applied to the methods of maximum likelihood, linear regression, and best linear estimators.

Popularity Index - 0%

Yen, C.S., and Dolan, T.J., A Critical Review of the Criteria for Notch-Sensitivity in Fatigue of Metals. (Univ. of Illinois Engineering Experiment Station, Bulletin Series No. 398, 1952). 209

Abstract

It is the purpose of this bulletin to summarize and to appraise critically the numerous interpretations or correlating methods that have been proposed in the technical literature to compare the endurance limits of notched rotating beam fatigue specimens with those of unnotched specimens. The interrelation of the ideas proposed by several investigators was studied. The discrepancy between theoretical and effective stress concentration factors is attributed to the fact that the structural action in real materials is different from that of a homogeneous, isotropic, elastic, "idealized material" commonly assumed in the theoretical analysis of stresses.

After surveying all relevant hypotheses it was summarized that notch-sensitivity of a metal member depends upon three different factors, namely: (a) the basic material characteristics, of which the localized work-hardening (or strain strengthening) capacity may be considered as an index; (b) the degree of material homogeneity, which is influenced by inherent defects, tensile residual stresses, heat treatments, etc.; (c) the geometry of the specimen (including over-all size), the radius at the root of the notch being of prime importance in this geometric factor. It was concluded that the criterion for fatigue failure or for endurance limit should include not only the peak stress at a critical point as is conventionally assumed, but also the conditions existing in a critical region surrounding the point. A rational approach and procedure for attacking the problem of notch effect as well as size effect is suggested.

Popularity Index - 0%

Yokobori, Takeo, The Statistical Aspect of Fatigue Fracture of Metals. (Reports of the Institute of Science and Technology, Tokyo, 8, 1, pp. 5-12, 1954. Applied Mechanics Review, No. 102, 1955). 210

Abstract

The previously reported data concerning two kinds of steel at three different stress ranges have been analysed. The number of specimens used was about seventy to hundred per stress range. The analysis used the method of plotting for the survivorship function proposed by Gumbel and independently by Weibull. When fatigue fracture is regarded as a problem of stochastic process, the survivorship function, p, is approximately given by the form

$$p = \exp(-NAS^{\gamma})$$

where A and γ are constants. The apparent incubation interval of repeated cycles is considered to correspond to the actual incubation interval during which dislocations pile up at obstacles, and to the apparent incubation interval which the micro-crack or crack nucleus takes in order to grow up to the macro-crack or lead to rupture of the whole specimen.

FRACTURE THEORY

ARMOUR RESEARCH FOUNDATION OF ILLINOIS INSTITUTE OF TECHNOLOGY

Fracture Testing of High-Strength Sheet Materials. Third Report of a Special ASTM Committee. (Materials Research and Standards, pp. 877-885, November, 1961). 211

Abstract

The purpose of this investigation was to establish accurately the type of notch specimen that should be used to measure fracture toughness of high-strength sheet materials.

Averbach, B. L., Interpretive Report of Project SR-136 to the Ship Structure Committee on Where We Stand In Design With Brittle Fracture. Massachusetts Institute of Technology, Cambridge, Massachusetts under Department of the Navy, Bureau of Ships Contract NObs-65918, BuShips Index No. NS-011-078, transmitted through Committee on Ship Steel, Division of Engineering and Industrial Research, National Academy of Sciences-National Research Council, under Department of the Navy, Bureau of Ships Contract NObs-72046, BuShips Index No. NS-731-036. (National Academy of Sciences-National Research Council, Washington, D.C., February 23, 1960). 212

Abstract

This review paper presents some of the highlights of the engineering features of brittle fracture together with a summary of some of the current theories, including the recent Cottrell Theory. In an attempt to interpret recent data in the light of the Cottrell theory it is concluded that some modifications in the theory are required to explain recent experimental results. Nevertheless, the dislocation picture of brittle fracture has been very helpful in providing a theoretical framework for the fracture mechanisms, and it is expected that these concepts will be continually developed with more theoretical and experimental work.

Backofen, Walter A., and Ebner, Merrill L., Metallurgical Aspects of Fracture at High Strength Level. Technical Report No. WALTR 310.24/5-2. For Watertown Arsenal Laboratories, Watertown, Massachusetts. Contract No. DA-19-020-ORD-5235. Ordnance Management Structural Code 5010.11.843, Department 213

of the Army Project No. 5B93-32-004. (March, 1962).

Abstract

Part 1: Fracture Toughness of Hardened and Tempered AISI 4340 Sheet

The fracture toughness, K_C, of quenched and tempered sheet specimens of air-melted and cross-rolled AISI 4340 was measured by procedures basically in accordance with those recommended by the special ASTM Committee on Fracture Testing. Fracture toughness, K_C, was obtained from the elastic analysis of Irwin, with and without the plastic-zone correction, and by the elastic-plastic analysis of McClintock. The two values calculated from the Irwin analysis are essentially the same for specimens tempered at 700° F. K_C values calculated according to McClintock agree within 20% with the corrected Irwin values for specimens tempered between 500° F. and 800° F.

Comparison of the K_C values with those of Rawe indicate that K_C for AISI 4340 is very sensitive to processing history. Extensive splitting, or delamination, along the plane of the sheet was observed in all fractures. It is suggested that this delamination, which is an event related to processing history, might contribute to low plane-strain fracture toughness and high toughness-transition temperature.

Part 2: Effect of Austenitizing Temperature on Fracture Mode of AISI 4340

Face-notched specimens of AISI 4340 were austenitized at 1550° F. or 2300° F., quenched, refrigerated, tempered, and broken in impact bending. The character of the fracture surfaces was observed in relationship to austenitizing temperature, tempering temperature, and testing temperature. When fracture did not occur along prior austenite grain boundaries, the surface appeared rougher (presumably associated with greater fracture toughness) for the larger grained material austenitized at 2300° F., regardless of the tempering or testing temperature. Preliminary fracture-toughness measurements agree with these fractographic observations.

Battelle Memorial Institute, Selected References on Brittle Fracture. DMIC Memorandum 55. (Defense Metals Information Center, Columbus, Ohio. May 5, 1960). 214

Berenbaum, R., and Brodie, I., Measurement of the Tensile Strength of Brittle Materials. (British Journal of Applied Physics, 10, pp. 281-287, June, 1959). 215

Abstract

Three alternative methods for measuring the tensile strengths of brittle materials are investigated and compared with the conventional pull method. These are a bending test, an indentation test, and a test in which disks are compressed diametrally. Experiments on plaster of Paris, coal, and cement show that, apart from the bending test, the methods give results in reasonable agreement. The bending test, however, is liable to give considerably different results, and it is shown that this can be attributed to its sensitivity to surface conditions.

Bikerman, J.J., and Passmore, G.H., Strength and Elasticity of Glass Fibers. (Glass Industries, 29, p. 144, 1948). 216

Abstract

The ultimate tensile strength, the total elongation, and the modulus of elasticity of commercial glass filaments have been measured, and the results subjected to a statistical analysis. It is found that, whereas Young's modulus of a fiber is almost independent of its length, the ultimate tensile strength is the greater, the shorter the filament. The relation between the strength and the length of a specimen is quantitatively accounted for by the greater probability of a weak spot in a longer specimen. Since Young's modulus does not show dependence on the fiber diameter, it is very unlikely that fine filaments have a molecular texture different from that of glass in bulk. The high strength of fine filaments probably is due to the favorable orientation of the "flaws" in drawn specimens, the act of drawing being more important than the reduction in diameter.

Bridgman, P.W., The Effect of Hydrostatic Pressure on the Fracture of Brittle Substances. (Journal Applied Physics 18 2, p. 246, 1947). 217

Abstract

An arrangement is described permitting the fracture of brittle materials under the action of tensile stress superimposed on hydrostatic pressure. The hydrostatic pressures range up to 30,000 kg/cm^2. The tensile stress superposed on the pressure required to break Pyrex glass is a strong function of the material by which pressure is transmitted to the lateral surface of the glass, but in all cases of fracture produced at pressures above 25,000 kg/cm^2, the net stress at fracture was compressive, that is, tensile fracture takes place against the direction of the stress. Beryllium and phosphor bronze lose the brittleness which characterize them at atmospheric pressure and fracture in tension under pressure after

marked plastic deformation. Carboloy remains brittle in tension under pressure, but its tensile strength may increase by a factor of three. NaCl elongates plastically in tension under pressure with no obvious disturbance of the optical homogeneity. Pipestone remains completely brittle under pressure and of very low strength. In simple compression combined with hydrostatic pressure, Pyrex glass increases greatly in strength. Single Crystal Al_2O_3 under the same conditions exhibits plastic slip on the basal plane without fracture. In the discussion the importance of the condition of energy release as a factor controlling fracture is emphasized. The Griffith conception of fracture as resulting from stress concentration at the ends of microscopic cracks is consistent with many qualitative aspects of the situation, but probably cannot be carried through quantitatively.

Bridgman, P. W., Fracture and Hydrostatic Pressure. (Fracturing of Metals, pp. 246-261, Cleveland, ASM., 1948). 218

Abstract

A discussion of some of the phenomena of fracture which occur when high hydrostatic pressure constitutes an important part of the stress field. The phenomena exhibit a wide variety and are often not what ordinary experience might lead one to anticipate. In varying the hydrostatic pressure under which fracture occurs we are in effect introducing another parameter, no less important than the temperature parameter, and in fact, capable of producing much more drastic alterations in the phenomena of fracture.

Card, Jr., David C., Review of Fracturing Theories. (Colorado School of Mines Research Foundation, Inc., Golden, Colorado. UCRL-13040, April, 1962). Prepared for University of California, Lawrence Radiation Laboratory. 219

Clarke, F.J.P., and Sambell, R.A.J., Micro-cracks and Their Relation to Flow and Fracture in Single Crystals of Magnesium Oxide. (Phil. Mag. 5, 55, p. 697, July, 1960). 220

Abstract

Evidence on mechanisms of fracture in magnesium oxide single crystals subjected to tensile loading is given. As cleaved crystals contain micro-cracks typically 10^{-4} inches long, and slip originating from near these cracks occurs during deformation. At a later stage the cracks grow

gradually until they increase to a critical size when catastrophic propagation occurs. If the cracks are removed by polishing, ductility is enhanced five to ten times. Some crystals were reactor irradiated to doses in the range 10^{14}-10^{19} n. v. t. (epithermal) and the effects of this treatment on flow and fracture are described and discussed.

Coffin, Jr., L. F., The Flow and Fracture of a Brittle Material. 221
(Trans. A.S.M., 72, pp. 233-248, September, 1950).

Abstract

The mechanism of flow and fracture of a gray cast iron can be understood if one considers the microstructure to consist of a ductile structure with a random dispersion of cracks due to the graphite flakes following the concept of Fisher. A notch effective stress can be calculated for a critically situated crack by a knowledge of the external stresses, a plastic stress-concentration factor of 3, and a residual tensile stress at the sharp edge of the crack, based upon either the "maximum-shear" theory or the "distortion-energy" theory. This allows the formulation of generalized plastic stress-strain relationships and renders gray cast iron applicable to the many known solutions for plastic flow of ductile metals. Fracture in the region of tension-tension and tension-compression can be evaluated by a similar analysis, using the same stress-concentration factor and the same residual stress. A combined stress-testing program is described wherein thin-walled cast iron tubes are subjected to two-dimensional states of combined stress covering the complete two-dimensional field.

Cottrell, A. H., Theory of Brittle Fracture in Steel and Its Application to Radiation Embrittlement. (UKAEA Industrial Group, Report 145 RD/C, H. M. Stationery Office, Paper No. 1, pp. 3-17). 222

Abstract

Brittleness in Metals. A conference held at R and D Branch Culcheth Laboratories, November 1, 1957.

Cottrell, A. H., Theory of Brittle Fracture in Steel and Similar Metals. (Trans. AIME 212, p. 192, 1958). 223

Abstract

Since metallurgy exists to provide strong, tough, engineering materials, it must inevitably be perpetually concerned with the problem of

brittleness. The steel-making industry was created because chemically unrefined iron is brittle. The steel-working and alloy-steel industries exist partly because hardness and ductility are mutually exclusive qualities in structurally unrefined steel. Yet, in spite of these immense industries, the brittle failure of steel ships hulls, bridges, pressure vessels, and pipelines, is still a contemporary problem.

Brittleness is a normal property of most solids, including metals and alloys, at low temperatures. Only face-centered cubic metals are commonly ductile at the lowest temperatures, and even here exceptions are known. Expensive arc-melting processes, under inert gases or vacuum, have been developed to overcome brittleness in titanium, zirconium, columbium, and molybdenum. Polycristalline zinc, magnesium, and uranium have little ductility at room temperature. Beryllium, chromium, and tungsten have even less; similarly for antimony, bismuth, germanium, silicon, intermetallic compounds, and metallic carbides, nitrides, silicides, and borides. Oxides and other ceramics would be ideal creep-resistant materials but for their extreme brittleness when cold, and great efforts have been made to overcome this problem by mixing ceramics with metals. In fact, the traditional use of the name metallurgy for what is really the science of engineering materials is a recognition that most nonmetallic solids have so far been precluded, by their extreme brittleness, from use as major structural materials in mechanical engineering.

Most of what we know about brittleness in metals has come from studies of structural steel, and it is this material that shall mainly be considered. The things we have learned from it have a wider application, at least to other body-centered cubic transition metals, although the extent to which similar ideas can be applied to hexagonal metals and other materials is not yet clear.

Cox, S. M., A Kinetic Approach to the Theory of the Strength of Glass. (Journal of the Society of Glass Technology, 32, p. 127, 1948). 224

Abstract

A theory of the strength of glass based on the kinetic energy of the atoms has been developed on the assumption that, if the thermal energy of the atoms is distributed in accordance with the Maxwell-Boltzmann law, there is a finite probability of some of the atoms having sufficient energy to cause a local discontinuity with consequent local stress enhancement.

Davidenkov, N.N., and Stavrogin, A.N., On Strength Criteria During Brittle Destruction and Plane Stressed State. (Isvestiya 225

Akademii Nauk SSSR, Otdeleniye Tekhnicheskikh Nauk, No. 8, 1954, pp.101-109. English pages: 16).

Davis, Harmer E., Parker, Earl R., and Boodberg, Alexander, A Study of the Transition From Shear to Cleavage Fracture in Mild Steel. (Trans. ASTM, 47, 483-499, 1947). 326

Abstract

Over ranges of temperature within which there occurred the transition from ductile shear-type failures to brittle cleavage-type failures, three types of specimens of three mild steels were tested: unnotched cylindrical tension bars, 3-inch wide flat bars with saw-cut notches in each edge, and 12-inch wide plates with a central notch at the midsection. The mechanism of fracture is discussed in relation to the variation in shear and cleavage strength with temperature and to the state of stress as induced by notching or deformation. Prestraining at a higher temperature was found to have an important influence on the cleavage strength which in turn affected the ductility at low temperatures. Depending upon the severity of the notch, through its influence on the state of stress and on the extent of plastic deformation before a crack is developed, the transition temperature of a mild steel may range from normal atmospheric to that of liquid air.

Dollimore, D., and Gregg, S. J., The Strength of Brittle Solids. (Research, pp. 180-184, May, 1953). 327

Abstract

The strength of a brittle solid is much less than the value calculated from other known properties of the solid, and moreover it is often less if measured in the presence of a vapour than in vacuo. Both phenomena can be explained along the lines of the Griffith crack hypothesis, but the effect is best understood in terms of the swelling produced by the sorption of the vapour, rather than in terms of the reduction in surface energy consequent on sorption.

Dorn, John E., The Effect of Stress State on the Fracture Strength of Metals. (Symposium - Fracturing of Metals, ASM, 1948). 328

Abstract

1. It is believed that metals fracture when a critical state of stress is reached; but the stress level for fracture depends upon many factors, such as anisotropy and the stress and strain histories preceding fracture.

2. Some metals (high strength aluminum alloys and also magnesium alloys) appear to fracture almost in accordance with a Shear Stress Law over the tension-tension and the tension-compression fields of biaxial stresses. Cast iron, however, appears to fracture principally in accordance with a Normal Stress Law over one range of biaxial stresses and a Shear Stress Law over other ranges of biaxial stressing. Present knowledge on the fracture laws for steels is inconclusive but the author believes that existing evidence appears to disqualify the Normal and Hydrostatic Tension Stress Laws and favor the Maximum Shear Stress Law.

3. Many factors affect the stress level for fracture; among these factors are the strain and stress histories preceding fracture. Complete agreement has not been reached among the various investigators on the trends of these effects. It appears that the hydrostatic tension stress history decreases the fracture stress and that the effective strain (octahedral shear strain) history increases the fracture stress in the absence of changes in stress ratios and reversals of stress.

4. Initial anisotropy is a major factor in modifying the stress levels for fracture in most commercial metals. Induced anisotropy resulting from the strain history preceding fracture is also an important factor.

5. Additional extensive investigations on the fracture of metals are required in order to clarify some of the questions that have been raised.

Drucker, D.C., Mylonas, C., and Lianis, G., Exhaustion of Ductility of E-Steel in Tension following Compressive Prestrain. (Welding Journal Research Supplement, March, 1960). .79

Abstract

Cylindrical bars of project E-steel were precompressed from 10 to 47%. Unnotched 0.505 tensile specimens were machined from the precompressed bars. Some were kept cold to prevent aging, some were aged under load, and some aged without load. All were tested at an ambient temperature of approximately 80° F.

The reduction of ductility which occurred in most of the cases was appreciable. In three of the specimens it was spectacular. One of the three suffered a complete tensile fracture on a cross-sectional plane at a strain of less than 2%.

Eldin, A.S., and Collins, S.C., Fracture and Yield Stress of 1020 Steel at Low Temperatures. (Journal of Applied Physics, 22, p. 1296, 1951). 23.

Abstract

The large helium refrigerator recently completed at the Massachusetts Institute of Technology has been equipped with a tensile testing machine capable of applying loads up to 60,000 pounds. A series of investigations of some of the mechanical properties of metals at low temperatures has been planned. The first project undertaken and herewith reported was the result of a suggestion by Professor E. Orowan of the need for measurements of brittle strength as a function of temperature.

Elliott, H.A., An Analysis of the Conditions for Rupture Due to Griffith Cracks. (Proceedings Physics Society, London, 59 (PT 2), pp. 208-223, 1947). 23.

Abstract

The solutions for the problem of an infinite isotropic elastic solid stressed under tension T_o and containing a single internal crack of length c on the plane $z = 0$ are given in a form suitable for the computation of the stresses and displacements at all points. These are used to find the stress distribution on, and the displacements of, the plane situated $a/2$ from the plane containing the crack. The normal stress σ_z on $z = a/2$ (as found above) is plotted as a function of $f(2u_z)$ of the normal displacement u_z, and τ_{rz} is small compared with σ_z.

A model is used in which the crack is considered to be bounded by the atoms centred on the planes $z = \pm a/2$, these planes being the boundaries of two semi-infinite elastic solids. Equilibrium is maintained by postulating that an attractive force, f(z), acts between the atoms of these bounding planes when they are $z + a$ apart. It is found that f(z) approximates to the law of force expected from atomic considerations, and the condition for unstable equilibrium of the crack, i.e., a value T_o^c of T_o such that $T_o < T_o^c$ the crack closes (c decreases), and for $T_o > T_o^c$ the crack spreads (c increases), is found. The surface energy is calculated from the results and the equilibrium condition is found in a form similar to that of Griffith. Agreement is found with the experimental results of Griffith.

In the absence of the tension T_o, the crack cannot be maintained without an inclusion to prevent closing. Possible physical models are discussed.

Elliott, Rodney P., The Energetics of Crack Formation and Propagation. (Wright Air Development Division, Air Research and Development Command, United States Air Force, Wright-Patterson Air Force Base, Ohio. Aeronautical Research Laboratory, Contract No. AF 33(616)-6148, Project No. 7024, April, 1960). 232

Abstract

As in body-centered cubic metals, brittle fracture characteristics of copper-zinc gamma brass in the temperature range immediately below the ductile-brittle transition temperature are governed by dislocation coalescent mechanisms. The Arrhenius-type relationship is obeyed at low fracture loads indicating that statistical energy fluctuations are contributory to brittle fracture. The systematic variation of the ductile-brittle transition temperature with strain rate and grain diameter is in agreement with previously developed theories. The relationship of σ_o as a function of temperature was ascertained to be logarithmic; however, the experimental data were obtained over too restricted a temperature range to permit ascertaining the exact temperature function involved. Fracture of gamma brass 200°-400° below the ductile-brittle transition temperature appears to be by a cleavage mechanism.

Elliott, R. P., and Metcalfe, A. G., The Energetics of Crack Formation and Propagation. (Quarterly Progress Report No. 1, December 1, 1958 to February 28, 1959, Project No. B 167, Contract No. AF 33(616)-6148, AF Project No. 7021, Task No. 70627, for Aeronautical Research Laboratory, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio). 233

Abstract

When a stress is applied to a brittle material, a crack is formed by a process which is as yet unresolved. At stress levels near a critical value thermal fluctuations possibly contribute to fracture. Therefore, Arrhenius type equations should be followed. This experimental program has been conceived to investigate the role played by thermal energy in the genesis of fracture.

Five alloy systems have been investigated as sources of room-temperature brittle compounds. These have been successfully extruded to wire at temperatures near their melting temperatures. Gamma brass and

$MgZn_2$ offer excellent possibilities as materials for investigation. Currently, methods are being investigated for gripping the specimens for tensile testing.

Feely, Jr., F.J., Hrtko, D., Kleppe, S.R., and Northup, M.S., Report on Brittle Fracture Studies. (Welding Journal Research Supplement, 99s-111s, 1954). 234

Abstract

This paper covers progress to date on brittle fracture studies being conducted in the Standard Oil Development Company, Esso Engineering Department Laboratories. These studies were undertaken to investigate the cause of failure of two large oil storage tanks in England in the spring of 1952. The object is to determine what can be done to insure against similar tank failures in the future.

The investigation has covered the broad field of possible causes of tank failures and definite steps have been taken by our company to improve the quality of welding through the use of radiographic examination. At the same time, a laboratory program was begun to determine whether the use of better steel was the ultimate solution to the brittle fracture problem.

From the beginning of the laboratory program, emphasis has been placed on developing a test to simulate conditions at the time of the tank failure. The paper outlines the steps taken in developing this test, and, in particular, studies of the effect of changing specimen size, geometry, notch acuity, impact, and other test variables. A comparison is made showing the close agreement between test results and actual conditions at the time of failure, using steel from the two tanks which failed in England. Finally, a correlation is made between the test results and fundamental physical properties of the materials tested.

Fisher, John C., A Criterion for the Failure of Cast Iron. (ASTM Bulletin, No. 181, pp. 74-75, 1952). 235

Abstract

It has been suggested that metals always undergo plastic deformation before they break. According to this viewpoint, cast iron and other brittle metals break as soon as they flow. Fracture stresses therefore must be identical with those required to initiate flow. The distortion-energy flow criterion, applied to regions of concentrated stress near

graphite plates embedded in the iron matrix of cast iron, leads to calculated yield stress values that are in reasonable agreement with experimental combined stress-fracture values.

Fisher, J.C., and Hollomon, J. H., A Statistical Theory of Fracture. (American Institute of Mining and Metallurgical Engineers. Technical Publication No. 2218, Classes C and E, Metals Technology, August, 1947). 236

Abstract

The fundamental problem concerning the fracture of both crystalline and noncrystalline solids is the divergence between the actual and the theoretically computed fracture stresses; the stress required for fracture, computed from the forces between atoms, is many times that actually observed with commercially available materials. Computations have been made indicating that the theoretical fracture stress should be from 100 to 1000 times that actually observed. There are other incidental problems that have arisen, perhaps the most important of which is the problem of size effect often observed in the measurement of the fracture stress of non-metallic solids, such as glass. Another effect concerns the relation between deformation and the stress required for fracture.

Frocht, Max M., The Behavior of a Brittle Material at Failure. (Journal of Applied Mechanics, 3, pp. A90-A103, 1936). 237

Abstract

This paper reports a number of unusual and instructive fractures and shows that the strength of bakelite, which may be considered a typical brittle material, is determined by the maximum tensile stresses as computed by advanced methods of stress analysis. The material used in the tests here described was obtained from the Bakelite Corporation of America and is known by the numbers BT-61-893 and BT-46-001.

Gilman, J.J., Creation of Cleavage Steps by Dislocation. (Trans. AIME, 212, p. 310, 1958). 238

Abstract

By comparing cleavage-step patterns and dislocation etch-pit patterns in LiF crystals, it is shown that screw dislocations always produce cleavage steps on fractured surfaces. Edge dislocations do not have

this effect. Using cleavage-step patterns as a tool, the phenomenon of crack nucleation of dislocations was investigated. It was found that out of 32 kinds of crystals, cracks nucleated dislocations in 25 kinds, 5 cases were doubtful, and no evidence of crack-nucleated dislocations could be found in 2 kinds.

Gilman, J.J., Fracture of Zinc-Monocrystals and Bi crystals. 239
(Transaction of the Metallurgical Society of AIME, 212, p. 783, December, 1958).

Abstract

Tests of zinc monocrystals have shown that the fracture stress of zinc is reduced by as much as X100 by small amounts of prior plastic glide. Tests of zinc bicrystals have shown that the effect of a grain boundary on fracture depends markedly on the type of boundary. Symmetric boundaries have no effect on either plasticity or fracture. Antisymmetric boundaries raise the plastic resistance but do not reduce the fracture stress. Asymmetric boundaries cause marked embrittlement. It is shown that fracture begins along the glide plane of a group of blocked dislocations; not ahead of the group and not below it. This is consistent with the behavior of bubble rafts. A simple, approximate theoretical treatment is given which is qualitatively and semi-quantitatively consistent with the experimental results.

Gilman, J.J., Knudsen, C., and Walsh, W.P., Cleavage Cracks 240
and Dislocations in LiF Crystals. (Journal of Applied Physics, 29, p. 601, 1958).

Abstract

It is shown that dislocations are nucleated ahead of the tips of cracks that move slower than $\sim 6 \times 10^3$ cm/sec in LiF crystals. The motion of cracks that move slower than $\sim 3 \times 10^3$ cm/sec is unstable; that is, the velocity oscillates.

About 2×10^5 cm/sec is the terminal velocity for (100) cleavage cracks in LiF.

For constant driving force, cracks move more slowly in crystals with high dislocation densities than in relatively perfect crystals.

Gilvarry, J.J., Fracture of Brittle Solids. I. Distribution Function for Fragment Size in Single Fracture (Theoretical). (Journal of Applied Physics, 32, 3, p. 391, March, 1961). 241

Abstract

For single fracture of a brittle solid, the distribution function for fragment size is obtained on the basis of Griffith's theory of brittle strength (which postulates crack propagation when pre-existent flaws are activated by stress). Three assumptions are made: (a) Fracture proceeds by activation of flaws in the volume of the specimen, in fracture surfaces through the specimen, and in the edges produced by fracture surfaces, (b) the corresponding volume, facial, and edge flaws are distributed independently of each other when activated, and (c) activated flaws of a particular type are distributed at random, individually, and collectively, in the sense of Fry. These assumptions yield directly and uniquely the probability dp(l, s, v) of formation of a fragment with total edge length, total face area, and total volume in the ranges l to l+dl, s to s+ds, and v to v+dv, respectively, as $e^{-Q}dQ$ in the general case, with Q linear in l, s, and v. The derivation yielding this Poisson form requires no assumption on the shape of a fragment or the type of fracture surface. The number dn(l, s, v) of fragments with total edge length, total face area, and total volume in the ranges l to l+dl, s to s+ds, and v to v+dv, respectively, is evaluated as the product of dp(l, s, v) by the a priori number q of particles with these values of l, s, and v. The distribution function dn(l, s, v) meets the necessary physical requirement that the fracture process conserve volume independently of particle shape. By assuming that all fragments are geometrically similar, one can replace dp(l, s, v) and dn(l, s, v) by forms, p(x)dx and n(x)dx, respectively, which depend only on a mean linear dimension x of a fragment. The resulting expression for y, the cumulative fraction of the initial volume corresponding to fragments of dimension up to x, then yields rigorously forms of the empirical equations of Schuhmann, and of Rosin and Rammler for this quantity, as limiting cases for x small. The conclusion follows that activation of edge flaws represents the dominant mode of fragmentation, in general. The moments of the distribution corresponding to the total number, the total edge length, and the total surface of the fragments are divergent; this anomaly is explained as the result of neglect of flaw depletion.

Gilvarry, J.J., and Bergstrom, B.H., Fracture of Brittle Solids. II. Distribution Function for Fragment Size in Single Fracture (Experimental). (Journal of Applied Physics, 32, 3, p. 400, March, 1961). 242

Abstract

The theoretical results of Gilvarry for the size distribution of the fragments in single fracture have been verified experimentally by fracturing spherical glass specimens under compression. The fragments were contained by a gelatin matrix to inhibit secondary fracture and thus make conditions conform as closely as possible to single fracture. Experimental values of the probability of fracture as obtained by sieve analysis show the predicted linear variation with the mean dimension x of the particles, over reasonably large intermediate ranges of the variables. It is shown that a logarithmic normal distribution does not represent the experimental results. The over-all data exhibit three local maxima in the differential probability of fracture as a function of x, whereas the theory permits only two. Agreement in the number of peaks is obtained by subtracting the contribution to the over-all probability of those fragments containing original surface of the specimen, which yields the true probability considered in the theory. In this manner, reasonably complete agreement between theory and experiment for single fracture is obtained. For plural fracture (carried out without use of gelatin), two additional peaks exist in the curve of the over-all differential probability vs x, as compared to the case for single fracture. The theory of Gilvarry is confirmed down to a fragment dimension of at least 1 μ by means of an electrical counting instrument, and checked by direct microscopic sizing to 5 μ. The results yield numerical values of internal flaw densities, and thus provide a tool to study the distribution of Griffith flaws existing internally in a solid.

Gooding, E. J., Investigations on the Tensile Strength of Glass. 243
(Journal of the Society of Glass Technology, 16, p. 145, 1932).

Abstract

The description is given of an apparatus used to determine the tensile strength of glass specimens of approximately 1 mm. diameter, the specimens having constrictions at their centres. These constrictions were formed in an electrically heated tube at a determined temperature. It was found that the type of fracture obtained, the thickness of the specimen, acid polishing the specimens, and matt etching the specimens considerably affected the tensile strength values, but that the influence of different loading methods, the temperature of constriction formation, the presence of strain, and the influence of sulphurous fumes during annealing were very small, if existent.

Experiments were made to attempt to correlate tensile strength and thermal endurance results.

The conclusion was drawn that the presence of surface flaws in glassware, as proposed by A. A. Griffith, would explain the results obtained.

Gordon, J.E., Marsh, D.M., and Parratt, Margaret E.M.L., 244
On the Strength and Structure of Glass. (Proceedings Royal Society, London, 65, p. A249, 1959).

Abstract

The strength of glass is known to be very variable and also to be affected by the condition of the surface. By improving a technique of decoration with sodium, due originally to Andrade, elaborate crack systems have been revealed on the surface of drawn glasses. These crack systems are correlated with, and may control, the mechanical strength of glass. They also appear to indicate the existence of a tension layer on the surface of glass. The cracks seem to be 100 to 200 Å wide and are probably at least 1000 Å deep. Cracks can be initiated by local abrasion, but this is probably not the only cause. A technique for the examination of thin glass films by transmission electron microscopy has also been developed and has been used to observe the mechanism of devitrification in various glasses. The initiation of cracks in fine crystallites has been watched and such cracks have been seen to propagate from the crystalline to the glassy regions in silica. It is, therefore, possible that fine-scale devitrification on the surface of glass during drawing might provide an alternative mechanism to abrasion for the origin of the surface cracks.

Grassi, R.C., and Cornet, I. Fracture of Gray-Cast-Iron Tubes 245
under Biaxial Stresses. (Journal Applied Mechanics, 71, p. 178, 1949).

Abstract

The fracture of gray-cast-iron thin-wall tubes was investigated, for various ratios of axial to tangential stress ranging from pure tension to pure compression, yielding data for some stress ratios not previously reported. Analysis of the results reveals that the present theories of fracture do not account completely for the data obtained, thus indicating the need for further investigations of similar materials.

Greenough, G.B., Cleavage Fracture in Hexagonal Metals. 246
(UKAEA Industrial Group Report 145 (RD/C). H.M. Stationery Office, Paper No. 9, pp. 44-45).

Abstract

Brittleness in Metals. A conference held at R and D Branch Culcheth Laboratories, November 1, 1957.

Griffith, A.A., The Phenomena of Rupture and Flow in Solids. 247
(Philosophical Transactions Royal Society, 221A, p. 163, 1920).

Abstract

In the course of an investigation of the effect of surface scratches on the mechanical strength of solids, some general conclusions were reached which appear to have a direct bearing on the problem of rupture, from an engineering standpoint, and also on the larger question of the nature of intermolecular cohesion.

Griffith, A.A., The Theory of Rupture. (Proceedings First In- 24
ternational Congress Applied Mathematics, Delft I, p. 55, 1924).

Abstract

The fundamental conception of the new theory is this. Just as in a liquid, so in a solid the bounding surfaces possess a surface tension which implies the existence of a corresponding amount of potential energy. If owing to the action of a stress a crack is formed, or a pre-existing crack is caused to extend, therefore, a quantity of energy proportional to the area of the new surface must be added, and the condition that this shall be possible is that such addition of energy shall take place without any increase in the total potential energy of the system. This means that the increase of potential energy due to the surface tension of the crack must be balanced by the decrease in the potential of the strain energy and the applied forces.

Gücer, D.E., and Gurland, J., Study of Fracture Strengths of 249
Sintered Carbides. (Department of Army Project No. DA-599-01-004, Ordnance R and D Project No. TB2-0001, OOR Project No. 2060, Contract No. DA-19-020-ORD-4888, June, 1960).

Gurland, J., The Fracture of Brittle and Quasi-Brittle Materials - 250
A Survey. (Department of Army Project No. DA-599-01-004, Ordnance R and D Project No. TB2-0001, OOR Project No. 2060, Contract No. DA-19-020-ORD-4888, August, 1959).

Abstract

A survey summarizing some of the prevalent views on the theory, behavior, testing, and design of brittle materials is presented. The survey is concerned first with the absence of plastic deformation and the origin of fracture, and then with a review of the problems of testing and the characteristic features of brittle behavior.

Gurney, C., Delayed Fracture in Glass. (Proceedings Physical Society, London, 59, p. 170, 1947). 251

Abstract

An important delayed-fracture effect is found for mineral glass. A likely cause might be the gradual spread of Griffith cracks, but a theorem due to Griffith states that cracks do not spread below a certain average stress, and that at this stress they spread catastrophically. In the present paper, Griffith's theorem is re-examined and it is shown that in materials having atomic constitution, fracture does not occur catastrophically at the Griffith stress; the Griffith stress is the least at which a crack may start to spread by a process of splitting, and the rate of spread is controlled by the rate at which thermal motions overcome energy barriers. Catastrophic fracture does not occur until the stress at the end of the crack equals the maximum a material can withstand. An improved method of estimating this stress from thermal data is given. The best estimate is that the maximum stress is equal to the intensity of the given stress system which makes the latent heat of evaporation zero. The rate of spread of cracks by Griffith's process is considered to be too slow to account for much of the delayed-fracture effect in glass. Other processes are considered under the headings of approach to homogeneous and heterogeneous equilibrium. The attainment of homogeneous equilibrium under stress in materials in equilibrium when stress-free involves, in the absence of phase changes, but a small entropy change, and is not likely to cause an appreciable time effect. Glass, however, is not in thermal equilibrium when stress-free, the high temperature phase persisting at temperatures below the transition point. On account of the high internal viscosity of glass, approach to equilibrium effectively ceases soon after manufacture. Stress reduces the internal viscosity and enables approach to equilibrium to continue. Because of the concentration of stress at the ends of the cracks, the approach to equilibrium made possible by stress is much faster in the material at the ends of the cracks than elsewhere, and as attainment of equilibrium involves volume shrinkage, the stress at the end of the crack is increased, and the crack spreads. This effect would be expected to cause an appreciable delayed fracture effect.

Two effects are considered under the heading of approach to heterogeneous equilibrium. The first is evaporation of the material at the end of the crack. An estimate of delayed fracture due to this cause suggests that it is unimportant. A much more important cause of delayed

fracture is atmospheric attack of the glass. Due to concentration of strain energy, the material at the end of the crack has a much higher free energy than normal unstressed glass, and is therefore much more chemically active. Atmospheric attack will result in the formation of a complex of glass and atmospheric constituents. The crack will extend continually if the strength of this complex, during or after its formation, is less than the load imposed on it.

Changes due to stress in the stable phase at room temperature are considered, but these are not likely to be important for glass, as in this material the high-temperature phase persists at room temperature. Phase changes under stress may have important effects on the behaviour of other materials. Included in the paper are formulae for the stress coefficients of vapour pressure, entropy, and phase-transition temperature, of material subjected to a generalized stress system.

Harkins, William D., Energy Relations of the Surface of Solids. I. Surface Energy of the Diamond. (Journal of Chemical Physics, 10, p. 268, 1942). 252

Abstract

From the known structure of the diamond the total surface energy of the crystal has been calculated in terms of the energy of the carbon-carbon bond, and is found to be: $1.50 \times 10^{-9} E_B$ erg cm^{-2} for the 111 face, and $2.10 \times 10^{-9} E_B$ erg cm^{-2} for the 100 face, where E_B is the energy in ergs per bond. If the bond energy is assumed to be 90 kcal. $mole^{-1}$ the values become 5650 erg cm^{-2} for the 111 face, and 9820 erg cm^{-2} for the 100 face. The corresponding free surface energies are found to be: 111 face at 25° = 5400 erg cm^{-2} 100 face at 25° = 9400 erg cm^{-2}. One uncertain feature in the calculation is that involved in the calculation of the decrease in energy caused by the long range binding of the valence bonds in the surface. In the 111 face the bonds are 2.517Å apart, and are perpendicular to the surface. Thus the bond directions are parallel, while inside the diamond the carbon-carbon distance is only 1.54A, and the bonds meet head on. While in the 111 face there is only one bond per carbon atom, in the 100 face there are two bonds per atom. In the 111 face there are 1.825×10^{15} bonds per sq. cm^{-2}, with an area of $5.48A^2$ each, while in the 100 face the corresponding values are 3.158×10^{15} bonds per cm^2 and $3.167A^2$ per bond. It is concluded that in the 111 face the interaction energy of the type described above is less than one percent and is negligible. Even in the 100 face the interaction should be small. No account was taken of any adjustment of the energy of the unsevered bonds in the surface region. This should cause a greater decrease of energy than the

long range binding of the severed bonds. Thus the values of the surface energy calculated in this paper should be considered as maximum values.

Harris, H., Problems of Brittle Fracture. (Iron and Coal Trades Review, pp. 1395-1399, December 12, 1958). 233

Abstract

In his presidential address to the West of Scotland Iron and Steel Institute (October 17, 1958), Dr. H. Harris (Babcock and Wilcox, Limited, Renfrew) discussed the present state of knowledge regarding the occurrence of brittle fracture with particular reference to the construction of pressure vessels. While there are still large gaps in our understanding, Dr. Harris suggests that with good design and workmanship there is no need to fear brittle fracture in the pressure vessels of atomic power stations.

Holland, A.J., and Turner, Professor W.E.S., The Breaking Strength of Glass. The Effect of Flaws and Scratches. (Journal of the Society of Glass Technology, 20, p.279, 1936). 234

Abstract

The influence of various factors on the bending strength of strips of flat drawn sheet glass, 0.26 to 0.285 cm. thick, 10 cm. long, and 0.8 cm. wide was investigated. A new diamond produced specimens which, when tested with the cut edges in tension, had a breaking strength of 570 kg./cm^2; for the worn diamond the value was 673 kg./cm^2. The nature of the cementing material when preparing, in blocks, specimens with sides ground and polished, was quite marked, values of the breaking strength 580, 877, and 938 kg./cm^2 being obtained when Canada balsam, shellac, and paraffin wax were used in the different tests made. Smoothing the edges with emery and then polishing with either pumice on wood or rouge on felt, reduced in general the breaking strength. When the edges of specimens were stoned and subsequently pumice-polished, however, a value of the breaking strength 1050 kg./cm^2, similar to that of specimens having their sides and edges fire-finished was obtained.

The depth of penetration of the residual flaws in the edges of specimens was correlated with the values of the breaking strength. Two straight line graphs were obtained, the one corresponding to those specimens with sides polished only, the other to those in which both sides and edges were polished. The straight lines converged to a value 1050 kg./cm^2, similar to that for fire-finished specimens free from flaws.

The effect of scratches in reducing the strength of glass was investigated, using as scratching tools a ground and polished conical dia-

mond 90°, and standard type H.M.V. half-tone gramophone needles. A diamond scratch of width 0.005 mm. reduced the bending strength from 877 to 505 kg./cm^2, and one of 0.0007 cm. width, which was invisible until etched, from 877 to 855 kg./cm^2. Consistent results were only obtained when using gramophone needles with loads less than 100 grams, the scratches being then invisible until etched with dilute HF. A scratch of width 0.0007 mm. was not effective in reducing the strength.

The evidence suggested that a scratch of width 0.001 mm. was needed to cause an appreciable reduction in the breaking strength.

Hollomon, John H., The Failure of Welded Steel Structures and Recommended Research. (Journal American Welding Society, Welding Research Supplement, pp. 534s-584s, September, 1946). 255

Abstract

Survey of the fracture problem to determine the practical significance of its research, its pertinence to the scientific knowledge now available, and the extent of co-ordination with the researches of other agencies.

The scientific analysis will not consist of a recitation of the known facts concerning fracture but will attempt to interpret the knowledge of fracture in terms of consistent theory. Where there are divergencies in knowledge they will be pointed out, and where theory is inadequate, an attempt will be made to indicate the direction of research to resolve the difficulty. The analysis to be presented will not necessarily represent the accepted interpretation of fracture, but rather it will often be a reflection of the author's point of view.

Holms, A.G., Empirical Correlation of Maximum Load Data from Published Brittle and Ductile Fracture Tests of Centrally Slotted and Centrally Loaded Plates and Sheets. (ASME Publication No. 60-WA-135, presented November 27 - December 2, 1960). 256

Abstract

A procedure is given for correlating maximum load data from tests of centrally slotted wide plates and sheets loaded to fracture in static tension. The procedure uses an elementary function of the initial specimen dimensions and the method of least squares to evaluate three empirical constants from a series of tests of specimens with the following conditions constant: (a) Material composition, (b) metallurgical processing, (c)

thickness, (d) notch radius at ends of slot, (e) temperature. The validity of the procedure was verified by checking it against published data where the properties of the materials varied widely including steels that fractured entirely by cleavage at low-temperatures, steels that changed fracture mode with specimen dimensions, and steel and aluminum alloys that fractured entirely in shear.

Homes, Georges A., and Gouzou, Jacques, Contribution to the Study of the Mechanisms of the Fracture of Metals. (Revue de Metallurgie, XLVII, No. 9, 1950).

Irwin, George, Fracture Dynamics. (ASM Symposium "Fracture of Metals", pp. 147-166, 1948).

Abstract

In this lecture the author will try to add some clarity to the dynamics of rapid fracturing in ductile metals.

Irwin, G. R., and Kies, J. A., Critical Energy Rate Analysis of Fracture Strength. (Welding Journal, Vol. 33, Research Supplement, pp. 193s-198s, April, 1954).

Abstract

In a recent article in this journal the writers discussed how engineering design and materials property controls for the onset of unstable fracturing might be established. The discussion given there was incidental to a more general discussion of fracturing and fracture dynamics. This paper gives a review of the simple mechanical concepts basic to an understanding of these unstable fracture control possibilities and discusses their applicability to large welded structures.

Irwin, G. R., and Kies, J. A., Fracturing and Fracture Dynamics. (Welding Journal Research Supplement, pp. 95-100, 1952).

Abstract

Fracturing begins at flaws and is accompanied by considerable

plastic deformation. The progressive extension of a fracture requires little driving energy which, however, may be assessed.

Ivlev, D. D., The Theory of Fracture of Solids. (PMM 23, 3, pp. 618-624, 1959). 261

Abstract

The present paper is concerned with the formulation of a theory of fracture of solids. The theory proposed is formal in character and is limited to the investigation of the simplest phenomological features of solids. It is a development of the ideas of Gvozdev.

Joffe, A., On the Mechanism of Brittle Rupture. (The Physical Society, London, 2, pp. 77-80, 1934). 262

Abstract

A considerable amount of experimental evidence is collected together to show that the weakness in tension of substances such as glass and quartz is due to irregularities on the surface. Thus it is well known that the strength decreases with increasing thickness; it is now shown that dissolving away a layer from the surface of a glass rod has the same effect as drawing it down in a gas flame. Again, the effect of the absorption of different vapours on the surface has been investigated. Other experiments show that irregularities of the kind postulated are distributed throughout the volume of the material, but that they only become harmful to the strength when they reach the surface.

The statistical distribution of strengths among a number of individual samples is in harmony with the theory, as also is the effect of altering the length of the sample.

The highest value found for the strength of rock salt is 160 kg. mm^2 as against the normal value of 0.4 and the theoretical one of 200.

Kochendörfer, A., Relation Between the Dislocation Energy of the Surface Energy Constants and the Elastic Constants of Crystals. (Naturwissenschaften 41, p. 36, 1954). 263

Lipson, Charles, Why Machine Parts Fail. (Machine Design, May-December, 1950). 264

Abstract

Fracture Analysis is a valuable design tool. It is a deductive process, originating with a broken part and terminating with a definition of the causes of failure. Heretofore, no comprehensive guide to fracture analysis has been available to the designer. To fill this need, Dr. Lipson has drawn from his wealth of experience in preparing an extensive series of articles of which this is the first. We are proud to present this noted authority's pioneering work.

Low, Jr., J.R., Observations on the Brittle Fracture of Cemented Titanium Carbide. (Journal of Metals, Transactions AIME, pp. 982-984, August, 1952). 265

Abstract

The brittle fracture of a TiC-Inconel cermet at room temperature is shown to occur primarily as a result of the cracking of the larger carbide particles (at a tensile strain of approximately 0.3pct), followed by cracking of adjacent, smaller carbides and, finally, by the rupture of the Inconel matrix between cracked carbides (at a strain of~1.2 pct). No evidence was found for separation at the interface between carbide and matrix at any point in the fracture process.

Machlin, E.S., and Nowick, A.S., Stress Rupture of Heat-resisting Alloys as a Rate Process. (American Institute of Mining and Metallurgical Engineers, Technical Publication No. 2137, Class C, Metals Technology, February, 1947). 266

Abstract

One of the main criteria used to rate the heat-resisting properties of alloys is stress rupture. During a stress-rupture test a tensile specimen is held under a constant load at a constant temperature until it fractures. The chief measurement made during this test is the time required for rupture at the specific test stress and temperature. It was found empirically from a series of stress-rupture tests at a constant temperature that when the logarithm of the time for rupture is plotted against the logarithm of stress a straight line is obtained within experimental error. This method of showing stress-rupture data has been adopted by many

investigators and the NACA. By interpolation and extrapolation from these plots, values of the stresses required to rupture the specimens (the rupture strengths) in 10, 100, and 1000 hr are obtained for specific temperatures. Alloys are then rated for a particular application on the basis of their rupture strengths at the rupture life that most nearly represents the application.

Inasmuch as stress rupture is an important criterion in rating heat-resisting alloys, it would be advantageous to know the quantitative dependence of the time for rupture on stress, temperature, composition, and structure. In order to obtain this information, an investigation was made at the NACA Cleveland laboratory during the spring of 1945. The theory of rate processes was used because it has been found to apply to certain processes such as chemical reactions, viscous flow, and creep that occur at a definite rate for given conditions. It was thought that stress rupture was such a process. An equation was derived that gives, for a given composition and structure, the dependence of the time for rupture on stress and temperature. The investigation is part of a general program to provide information that will lead ultimately to the development of better alloys in order that the efficiency and power output of gas turbines used in aircraft propulsion can be increased.

Marin, Joseph, Working Stresses for the Rational Design of Concrete Structures. (Journal of Applied Physics, 9, 1, p. 49, 1938). 267

Abstract

This paper presents a new theory of failure for materials subjected to a combined state of stress. The theory is developed for brittle materials, such as concrete, in which the compressive and tensile strengths are of different magnitudes. It is a semi-empirical theory which has some experimental support. Based on it, working stresses are defined for various loading conditions. The use of these proposed working stresses in some cases makes considerable difference in design as compared to the present specifications requirements. These working stress values are conveniently represented by a diagram to facilitate the computations in design. The application of this information can be made simply in most cases where there are stresses acting in two right-angled directions - such as slabs in buildings, roads, and bridges, retaining walls, dams, and other hydraulic structures of concrete and reinforced concrete.

McClintock, F.A., Ductile Fracture Instability in Shear. (Journal of Applied Mechanics, 25, p. 582, 1958). 268

Abstract

It is postulated that fracture occurs in an elastic-plastic, nonwork-hardening material subject to pure shear when a critical shear strain is attained throughout a critical volume of material. This postulate is combined with the classical equations of plasticity to predict when cracking will initiate from a notch at nominal shear stresses below the yield stress, when the crack will become unstable on increase of stress, and when unstable cracking will occur if a notch is cut while a constant nominal stress is maintained. Tests on aluminum foil under biaxial tensile stress show results similar to those predicted by the theory.

Meyer, Jr., André J., Kaufman, Albert, and Caywood, William C., The Design of Brittle-Material Blade Roots Based on Theory and Rupture Tests of Plastic Models. (National Advisory Committee for Aeronautics, Technical Note 3773, September, 1956). 269

Abstract

Theoretical design charts based on Neuber's equations for symmetrically located notches are presented for estimating the approximate rupture strengths of blade roots made from brittle materials. The limit of applicability of the theoretical charts is shown as determined by rupture tests of plastic models. The optimum proportions among over-all root width, neck width, notch radius, and notch depth are determined from the design charts.

Eighteen different root designs were investigated, their relative strengths were evaluated analytically and experimentally, and the results were compared. A dovetail root having the optimum proportions as established by this investigation was the strongest root evaluated.

Mott, N. F., Fracture in Metals. (Journal of Iron and Steel Institute, 183, p. 233, 1956). 270

Abstract

My aim in this lecture is to discuss three types of fracture in metals, ductile fracture, brittle fracture especially of ferrous materials, and fatigue. I shall discuss fracture in terms of the theory of dislocations and I will begin by outlining this theory and showing some small part of the experimental evidence on which it is now based.

Murgatroyd, J.B., Mechanism of Brittle Rupture. (Nature, 154, p. 51, 1944). 271

Abstract

The low strength of brittle materials has been ascribed by A. A. Griffith to the presence of discontinuities which have the properties of small cracks in these materials. Since this theory was published, however, several investigations have established the fact that glass exhibits the phenomenon of delayed rupture to a marked degree, and this is not easily explicable by Griffith's theory alone.

As a result of investigations which will be published shortly, I have been led to the hypothesis that glass consists of an elastic matrix which contains small pockets of 'quasi-viscous' material. These pockets take the place of Griffith's 'flaws'; and when the glass is subjected to a stress the initial load carried by the viscous material is conveyed to the matrix as relaxation of the stress occurs in the viscous material. In this manner a stress concentration grows with time in the matrix surrounding a 'viscous pocket'. Finally, such a pocket would become the equivalent of a hole in the matrix when the viscous material carried no stress.

Murgatroyd, J. B., The Mechanism of Brittle Rupture in Glass. (Journal of the Society of Glass Technology, 28, p. 406, 1944). 272

Abstract

Griffith's "crack theory" and the weak molecular bond theory of the strength of glass are tested by strength phenomena recorded by different investigators, and it is concluded that modifications are necessary to these theories to account for the facts. The suggestion is made that Griffith "flaws" consist of pockets of quasi-viscous material surrounded by larger three-dimensional aggregates, and that when the pocket material has yielded to an applied stress the fact that it then carries no load makes the pocket the equivalent of a "hole" in the glass. Such a "hole" would act as a stress concentrator. In this way, the time elapsing before breakage occurs is explained as being due to the time required for the stress in the quasi-viscous material to relax. By means of a model representing the stress concentration at a pocket an equation is derived relating the breaking strength, P_B, with time, t. Values of the breaking strength calculated from this equation, $P_B - a = \frac{b}{tk}$, are in good agreement with published experimental results.

Mylonas, C., Prestrain, Size and Residual Stresses in Static Brittle-Fracture Initiation. (Welding Journal 38, 10, Research Supplement, pp. 414s-424s, 1959). 273

Abstract

The concept of exhaustion of ductility used in the explanation of the mechanism of static brittle-fracture initiation has led to the achievement of the first laboratory fractures of unwelded steel plates under central static loading at average net stress as low as 12% of virgin yield. The same concept and considerations of required vs. existing ductility provide a rational approach for the explanation of prestrain and of size effect in brittle fracture. Similarly they lead to a clear qualitative assessment of the varying influence of residual stresses and show that the usual localized residual stresses have little if any importance in normal structural steels.

Mylonas, C., Static Brittle Fracture Initiation without Residual Stresses. (Technical Report No. 4, Ship Structure Committee, Under Contract NObs-78440 with the Bureau of Ships, Department of the Navy, March, 1961). 274

Mylonas, C., Drucker, D.C., and Brunton, J.D., Static Brittle-Fracture Initiation at Net Stress 40% of Yield. (Welding Journal Research Supplement, pp. 473s to 479s, October, 1958). 275

Abstract

Static fractures which are brittle from the start are evidence of lack of ductility at the point of crack initiation and occur at low average net stress. Past static tests, in failing generally to reproduce the phenomenon of brittle-fracture initiation, showed that undamaged steel plate under adverse notch conditions has sufficient ductility to allow general yielding before fracturing. Static initiation of brittle fracture can be achieved by an additional exhaustion of ductility. For this purpose, a steel of high transition temperature was subjected to various types of prestraining. The best results were achieved by precompressing 3/4-inch thick 10-inch square plates with machined notches so as to produce large plastic strains at the notch roots.

When tested in central static tension at a temperature below the transition range, these plates fractured at average net stresses well below yield level. The lowest average stress at fracture was 36 % of virgin yield. Thus, for the first time brittle fracture of unwelded steel plate has

been initiated in the laboratory under controlled conditions at such low stress. The conditions at fracture indicate that energy theories are useless or inapplicable in the problem of fracture initiation. Finally, residual stresses are shown to be of little importance when ductility is ample. When embrittlement is excessive, they only hasten a fracture which would have occurred at low applied stress in the absence of residual stress.

Mylonas, C., Drucker, D.C., and L. Isberg, Brittle Fracture Initiation Tests. (Welding Journal Research Supplement pp. 9s - 17s, January, 1957). 276

Abstract

A running crack will propagate at nominal stresses of 10,000 psi in steel plate. Nevertheless, structures of such steel operate at higher nominal stress. Furthermore, laboratory tests generally fail to initiate brittle fracture at nominal stresses below yield except by extreme cooling or impact loading. A strong barrier to the static initiation of brittle fracture thus exists.

The object of the present investigation is to study the conditions under which this barrier is lowered. Until static laboratory tests reproduce fractures at the temperatures and nominal stresses encountered in service, brittle fracture will remain essentially unexplained.

Moderate success has been achieved so far. Welded and unwelded notched steel plates with various prestrains were pulled at various temperatures. Transversely prestrained plates with punched notches fractured consistently below yield under static loading. The fractures were as brittle as those found in service in the region of propagation and, far more important, also at the point of initiation.

Mylonas, C., and Rockey, K.C., Exhaustion of Ductility by Hot Straining - An Explanation of Fracture Initiation Close to Welds. (Welding Journal Research Supplement, pp. 306s - 310s, July, 1961). 277

Abstract

Plastic compression or extension reduced the ductility of steel far more when performed at a temperature around 500° F. than at room temperature. In particular, plastic extension at 450° F. drastically reduced the ductility in subsequent tension at -16° F. and resulted in brittle fracture after additional straining of only 0.02. This exhaustion of cold

ductility by hot extension occurs during the cooling of welded plates and provides an explanation of fracture initiation close to welds.

Mylonas, C., Conditions Favorable to the Initiation of Brittle Fracture. (No source recorded). 27

Abstract

Translated from the French. - A composition (or element of composition) in steel should be formed in such a way as to support without breaking the weight of average net stress, even in the presence of notches or fissures and of the resulting concentrations of constraints and plastic deformations. A fracture under the weakest stress (a brittle fracture) indicates that the parts strongly stressed are incapable of sufficient deformation to permit the stress to reach its full limit. It is evident that the susceptibility to brittle fracture can be judged by a comparison between the ductility necessary to reach the full stress and the ductility existing in the material in the required direction. At the same time, a great number of experiments have demonstrated that all the normal structural steels, even notched and at low temperature, have sufficient ductility in their new state to resist fracture at low applied stress. In fact, the fractures under weak stress must be induced with the aid of a violent shock, which overcomes the barrier of the initiation of fracture. This difference between laboratory tests and actual constructions which break under total stresses, very weak and purely static, indicate that this barrier, ordinarily high enough, under certain circumstances ought to be considerably lowered. It is demonstrated that a fundamental condition lowering this barrier and permitting the initiation of fracture under a weak stress is a local exhaustion of ductility.

O'Brien, John N., The Fracture of Metals under Impulsive Loading Conditions. (Quartermaster Research of Engineering Command, U.S. Army, Contract DA 19-129-QM-1166, O.I. No. 6140, Project 7-99-01-001, Office of Naval Research Contract Nonr-1866(35), December 20, 1961). 279

Abstract

A modification of the Hopkinson pressure-bar technique has been used to study the spalling of metals impacted with a compression shock-wave. It was found that the fracture began by the growth of cracks, and final failure occurred by the shear of metal separating crack tips. The

fracture is shown to occur not by the tearing apart of grain boundaries, nor by thermal nucleation of a fracture nucleus.

It will be shown that the fracture mechanism does not involve that proposed by von Karman for impact failure of rods. The fracture stresses of the pure metals are compared to calculated theoretical strengths and found to be about one-tenth of the theoretical strengths. It is shown that the effect of compression stress preceding fracture on the fracture stress, noted by earlier authors, is caused by attenuation. The two-wave structure which is found in shocked metals, due to the support of finite shear stresses, will be discussed. The two-wave structure will be taken into consideration in the calculation of the fracture stresses. Because of this two-wave structure, it is concluded that this technique is not as good for the study of high-strength alloys as it is for the study of pure metals.

Orowan, E., The Increased Strength of Thin Fibers, the Joffe Effect, and Related Phenomena from the Standpoint of Griffith's Theory of Fracture. (Eingegangen am 30, August, 1933). 230

Orowan, E., The Initiation of Brittle Fracture by Wedge Penetration. (Technical Report No. 5, Office of Naval Research, Contract No. N5ori-07870, July, 1954). 231

Abstract

1. Crack starting stress and crack driving stress.

There is a fundamental difference between the fracture of a completely brittle material such as glass and the brittle (cleavage) fracture of normally ductile low carbon steels. According to the available experience, the former process is fully governed by the Griffith crack propagation condition which, in the simple case of a large plate under a uniaxial tension stress σ, containing a relatively short edge crack of length c, has the form

$$\sigma \approx \sqrt{\frac{E\alpha}{c}} \qquad (1)$$

where **E** is Young's modulus and α the specific surface energy of the surface of fracture. The crack starts to propagate when the (mean) tensile stress in the plate reaches the value of the propagating ("driving") stress given by equation (1). If, in the course of its propagation, the mean stress rises above the value given by the Griffith equation, the crack accelerates;

in the opposite case, it decelerates. It can be shown that Equation (1) represents a necessary and sufficient condition of crack propagation in a fully brittle material.

Orowan, E., The Rupture of Plastic Crystals. (Proceedings of International Conference on Physics, The Physical Society, London, 2, p. 81, 1934). 232

Abstract

Sensitive processes start from nuclei (e.g. Griffith cracks for rupture or dust particles for condensation of a vapour). Their sensitivity is caused by two circumstances: (1) The intensity of the external influence (e.g. load or supersaturation as the case may be) necessary to start growth from the nuclei may depend considerably on their size (or quality). (2) The whole process may be initiated by a single nucleus or a few nuclei. An important difficulty of the crack propagation theory hitherto has been the enormous crack lengths required by the Griffith formula for explaining the technical strength of plastic crystals. Besides the statical notch-effect considered by Griffith, there exists, however, another possibility for the development of cracks by means of plastic slip. By taking this into account, the necessity of assuming unduly large crack lengths can be avoided. Thus the crack propagation theory is to be regarded as satisfactory. On the other hand, proofs are given showing that no secondary or block structure explanation of the technical tensile strength is possible.

Parikh, N.M., Cermets: III, Modes of Fracture and Slip in Cemented Carbides. (Journal of the American Ceramic Society, 40, 10, October, 1957). 233

Abstract.

The modes of fracture and slip in cemented carbides were observed. Fracture and slip patterns in cemented carbides were found to vary with the microstructures which in turn were determined by the relative surface energies of various phases. The influence of particle size and metal binder content in cemented TiC and WC was also investigated. The fracture and slip in these systems are discussed in terms of the role of the metal film surrounding the carbide grains.

Parrott, T. L., Experimental Studies of Glass Breakage Due to Sonic Booms. (Sound, 1, 3, p. 18, 1962). 234

Abstract

Sonic booms which result from shock waves generated by aircraft in supersonic flight have in some cases caused rather severe damage to ground building structures. The limited amount of available information suggests that the major portion of damage resulting from sonic booms is, however, of the nuisance type, such as glass breakage, cracked wall plaster, etc. It is the purpose of this article to present the results of a flight test program designed to produce information relating to window-glass breakage from sonic booms.

Paul, Burton, A Modification of the Coulomb-Mohr Theory of Fracture. (ASME paper No. 60-WA-31, Annual Meeting November, 1960). 235

Abstract

The inability of the Coulomb-Mohr theory of fracture to explain the main features of compression, tension, and torsion tests on brittle materials is pointed out. It is shown that the introduction of suitably chosen tension cut-offs and "friction angles" removes this deficiency and leads to a satisfactory explanation of the fracture stresses and angles of fracture for these three simple tests. The modified Coulomb-Mohr theory is a three-parameter theory, but all three parameters in principle can be obtained from only two simple tests. It is shown that in the case of cast iron there is an extremely close relationship between cohesive resistance in shear and nominal ultimate strength in single or double shear. The modified theory fits the data of Coffin, Cornet, and Grassi on biaxial fracture of cast iron very well. The three-dimensional fracture surface is described and used to explain some apparently anomalous points in the experimental data. Finally, a hypothesis is advanced which explains the appearance of concavities in the yield locus for certain classes of materials.

Pearson, S., Delayed Fracture of Sintered Alumina. (Proceedings of Physical Society, London, B, 69, p. 1293, 1956). 236

Abstract

The strength of sintered alumina, when tested in the normal atmosphere, is shown to depend on the time for which the stress is applied.

When stressed in bending under constant load, the average time to fracture increases from 1 sec to 10^6 sec when the stress is reduced by about 22%. This delayed fracture can be largely eliminated by heat treating and testing in a vacuum. The vacuum heat treatment does not change the strength of the material permanently since the delayed fracture effect reappears when the material is again exposed to the atmosphere. It is concluded that the effect is due to attack of the stressed material by constituents of the atmosphere.

Petch, N.J., The Cleavage Strength of Polycrystals. (Journal, Iron and Steel Institute, 174, p. 23, 1953). 237

Abstract

Using mild steel, ingot iron, and spectrographic iron, it is found that the cleavage strength σ_c is related to the grain size L by

$$\sigma_c = \sigma_o + k/\sqrt{L}$$

This can be explained if the Griffith cracks can be identified with glide planes on which dislocation movement has been blocked by the grain boundaries.

According to this theory, the cleavage strength of the polycrystals is controlled by the theoretical cleavage strength in the grain-boundary region, which opens up the possibility of subtle composition effects in this special region, by the grain size, which determines the stress-concentration factor, and by σ_o. The plastic strain at fracture is greater when the grains are finer and the strain-hardening rate is lower.

Petch, N.J., The Fracture of Metals. (Progress in Metal Physics, 1954). 238

Abstract

The basic problem in fracture is to find some factor that will account for the order of magnitude difference between the theoretical, and the observed strengths of real solids.

Polanyi, M., On The Nature of the Rupture Process. (Physik 7, pp. 323-327, 1921). 239

Poncelet, Eugene F., Fracture and Comminution of Brittle Solids. (American Institute of Mining and Metallurgical Engineers, Technical Publication No. 1684, Class B, Milling and Concentration, No. 156; Class C, Iron and Steel Division, No. 355; Class E, Institute of Metals Division, No. 424, 1944). 290

Abstract

Glass squares compressed on edge by steel jaws in poor contact with them developed jagged "partial-contact" cracks caused by the formation of local tensile stresses. Compressed by steel jaws in perfect contact, they developed smooth "release cracks" during release of the pressure, caused by the formation of local tensile stresses during the release of the pressure. All these cracks were parallel to the pressure.

A Microflash photograph of a disintegrating specimen under sufficient pressure reveals a network of fractures roughly normal to each other, also "release cracks", and a disintegration cloud.

The Griffith theory is amended to account for the formation of a first crack. A new theory, based on the theory of thermal agitation and wave propagation, is proposed to account for the progress, velocity, and forking of cracks. The network of fractures is shown to have been caused by reflection at a free boundary of pressure pulses emanating from a first crack.

Postulating equal distribution of energy in the pulses emitted on either side by a crack in particles, the smaller fragments are shown to continue fracturing preferentially while some of the coarser fragments remain as residual pieces. As comminution of the smaller fragments proceeds, the solid is reduced to a collection of residual particles of smaller and smaller sizes, accounting for the disintegration cloud.

Readey, W. B., An Investigation of the Definition of Missile Structural Design Criteria Requirements on a Reliability Basis. Part II. The Development of a Method Framework for Determining the Quantitative Structural Design Requirements Necessary to Achieve a Given Level of Structural Reliability. (Flight Dynamics Laboratory, Contract No. AF. 33(616)-6677, Project No. 1367, Task No. 13582, August, 1960. Wright Air Development Division, Air Research and Development Command, United States Air Force, Wright-Patterson Air Force Base, Ohio). 291

Abstract

A framework for a method for designing to a predetermined structural reliability is developed. Quantitative structural reliability of existing structures can also be determined by the method. A method for designing to a minimum weight for a given reliability, or to a maximum reliability for a given weight, is presented. An analog technique for checking any structural reliability method is described.

Although the method was developed primarily for structural reliability programs, it is equally applicable to the design of structural components in electron tubes, or almost any nonstructural reliability investigation. The scope of the method is so broad that its application could conceivably be extended to such remote areas as flood crest predictions, and determination of the probability of hitting a target area. Because of the wide scope and complexity of the problem, emphasis was on developing a sound foundation and no attempt at final refinement was made.

Ripling, E.J., and Baldwin, Jr., W.M., Overcoming Rheotropic Brittleness: Precompression versus Pretension. (Transactions ASM 44, pp. 1047-1057, 1952). 292

Abstract

The brittle behavior at low temperatures, high strain rates, and under severe notched conditions of metals not crystallizing in the face-centered cubic system have previously been shown to be largely strain curable; that is, rheotropic. In all the work on rheotropy to date, however, prestraining and testing were always both tensile strains in the same direction. In the present study it is shown that subtransition temperature tensile ductility is also improved by supertransition compressive prestrains in the same direction as the subsequent tensile strain. This eliminates the possibility that rheotropic recovery is simply a matter of realigning microflaws.

A difference in the temperature dependence of precompressed steel and aluminum is also pointed out.

Roberts, D.K., and Wells, A.A., The Velocity of Brittle Fracture. (Engineering, 178, p. 820, 1954). 293

Abstract

Terminal velocity shown to be a definite fraction of elastic-wave velocity.

Robertson, T.S., Experimental Techniques Developed in Investigations into High-Speed Yield in Brittle Fracture. (No Source Recorded). 294

Abstract

In his work on high-speed yield in brittle fracture, the author has done three things. He has taken high-speed photographs of large plates which are failing and from these high-speed photographs he has observed local yielding. He has at the same time placed on the plates high-speed wire resistance strain gauges so that he can make measurements on the straining that takes place at the time of fracture. Thirdly, he has made post-mortem examinations of the fractures and observed the nature of the fractured surface. From these three approaches, he has been able to piece all the results together and this has led to a new picture of the actual mechanism of brittle fracture.

Rostoker, W., Fracture of Metals. (Summary Report under Contract No. DA-11-022-ORD-3108, ORD Project No. TB 4-001, M219, June 8, 1959 to June 30, 1960, for Commanding Officer Frankford Arsenal, Philadelphia 37, Pennsylvania). 295

Abstract

Experiments are described which have been designed to demonstrate the role of surface or interfacial energy in the brittle fracture produced by wetting with a low-melting liquid metal. Such experiments have shown that the ductile-brittle transition temperature in alpha brass can be analyzed by the dislocation model for crack nucleation. Further experiments replicating the work of Orowan and Felbeck in crack propagation show that very low effective surface energies are involved. The difference in surface energies associated with crack initiation and propagation are discussed. Finally, the results of extensive studies of the relative propensities of grain boundary and grain center areas to crack initiation are presented.

Sachs, George, Effect of Strain on Fracture. (Symposium Fracturing of Metals, ASM, pp. 51-67, 1948). 296

Sack, R. A., Extension of Griffith's Theory of Rupture to Three Dimensions. (Proceedings Physical Society, London, 58, pp. 729-736, 1946). 297

Abstract

Griffith's theory of rupture of brittle materials is extended to materials containing circular cracks. It is found that (a) the tensile strength of brittle material in one direction is not affected by stresses at right angles to it; (b) the result differs from Griffith's by a factor depending on Poisson's ratio of the material and lying between 1·57 and 1·81.

Schardin, H., Fracture Processes in Glass. (Proceedings International Commission on Glass, 1, pp. 81-95, 1954). 298

Abstract

By using high-speed cinematography a particular value for the velocity of fracture in glass has been found. To evaluate the dependence of fracture velocity on glass composition, results have been determined for ten different Schott glasses. Another method of determining fracture velocity is by means of the Wallner lines found on the fracture surface. An initial fracture stage is indicated during which the fracture velocity increases from zero to the normal value. In other instances also a real or apparent deviation of fracture velocity from the normal value has been found. In particular, when rib marks and hackle marks appear at the same time, the behaviour is abnormal. A number of pictures taken with a multiple spark camera shows the formation of fractures in the case of impact against the edge of a glass plate and when a glass plate is tested in tension.

Schwartzberg, F. R., Ogden, H. R., and Jaffee, R. I., Ductile-Brittle Transition in the Refractory Metals. (Office of the Assistant Secretary of Defense for Research and Development. ASTIA AD 216526, OTS PB 151070, DMIC Report 114, June 25, 1959, Defense Metals Information Center, Battelle Memorial Institute). 299

Abstract

Ductile-brittle transition behavior occurs in the body-centered cubic refractory metals columbium, molybdenum, tungsten, and chromium. The available data for vanadium suggest that brittleness at low temperatures is attributable to low-strain-rate hydrogen embrittlement. However,

the occurrence of ductile-brittle transition behavior is not precluded. No brittle transition has yet been found in tantalum.

Transition temperature can be greatly influenced by testing and material conditions. As a general rule, the following factors increase the temperature at which the brittle transition occurs:

(1) Recrystallization
(2) Decreasing amounts of cold work
(3) Increasing grain size
(4) Increasing interstitial content
(5) Increasing strain rate
(6) Introduction of triaxial stresses.

The transition from ductile to brittle behavior is associated with a rapid rise in yield strength occurring with reductions in temperature. Brittle behavior is observed to occur when the yield strength equals the fracture strength. Cottrell's theory of dislocation locking by interstitial atoms is generally used to explain the yield-strength rise at low temperatures.

Shand, E. B., Experimental Study of Fracture of Glass: I. The Fracture Process. (Journal of American Ceramic Society, 37, (2), p. 52, 1954). 300

Abstract

A concept of fracture is developed from experimental data. Fractures are found to originate at flaws or cracks of finite size, most of which are at the surface. The mechanism is one of crack propagation which begins when the local stress at the crack exceeds a minimum value. The rate of propagation increases with crack growth until a critical stress is reached at the crack tip which coincides with a limiting crack velocity. This limiting condition is identified with the boundary of the mirror surface of the fracture. From calculations to be presented in Part II, the critical stress is estimated to be several million pounds per square inch.

Shand, Errol B., Experimental Study of Fracture of Glass: II. Experimental Data. (Journal of the American Ceramic Society, 37, 12, December 1, 1954). 301

Abstract

Original studies and experiments that support the concept of the close association between fracture origin and flaws in glass are presented.

The effect of temporary overstresses, fracture velocities during the later development of the process, and evaluation of the critical stress are discussed. Data are presented which show that temporary overstresses may weaken glass permanently and that this effect results from the slow propagation of fracture flaws. The study of fracture surfaces reveals that the velocity of the fracture crack across the section is not necessarily uniform and that the velocity characteristics of each individual fracture are determined by factors such as degree of load relaxation occurring during the dynamic phase of the process. The critical stress is estimated to be between 2.5 and 5 million pounds per square inch, and, for any particular glass, this stress is independent of test conditions.

Shank, M.E., A Critical Survey of Brittle Failure in Carbon Plate Steel Structures other than Ships. (Prepared for National Research Council's Committee on Ship Structural Design, Advisory to Ship Structure Committee, under Department of the Navy, Bureau of Ships Contract NObs-50148, BuShips Project NS-731-034, with the National Academy of Sciences - National Research Council, December, 1953). 352

Abstract

The failure of ships at sea and at dockside during World War II brought the problem of brittle fracture into sharp focus. Data from ship failures have been well correlated, and as a result, much has been learned from research stimulated thereby. No simular correlation on nonship failure data exists, and this survey was therefore undertaken in order to supplement the study of ship failures. A total of 64 structural failures, plus failures in gas transmission lines, was studied. These failures occurred in both riveted and welded structures such as tanks, bridges, pressure vessels, a smoke stack, a penstock, power shovels, as well as gas transmission lines. It is shown that the history of brittle failure extends back at least to 1879. It is concluded that: (1) Brittle failure in nonship structures is the same phenomenon as occurs in ships; (2) brittle failure occurs in many types of nonship structures; (3) brittle fractures can cross riveted joints; (4) there is no evidence to show that the percentage incidence of brittle failure has either decreased or increased with the advent of welding; (5) in conjunction with other factors, thermal stress may be important; (6) residual stresses are not the prime cause of brittle failure, but such stresses may, in conjunction with other factors, initiate such failure; (7) the effect of metallurgical variables is important; (8) cold forming promotes susceptibility to brittle failure, but its role cannot be assessed due to lack of data; (9) in such cases where data are available, Charpy impact values of plate were generally low at the

failure temperature; (10) in most cases of nonship brittle failure, the fracture originated at defects arising from fabrication. A few originated at design defects; (11) it seems evident in all cases that fracture originated at a geometric discontinuity; (12) no evidence exists for these failed structures to show the effects of various welding processes on susceptibility to brittle failure; (13) except in the case of exceptionally poor welds, there is no tendency for fracture to follow welded seams; (14) the great majority of nonship brittle failures apparently occur under conditions of entirely static loading; (15) age of structure seems to have no bearing on brittle failure; (16) most engineering codes permit the use of steel which is known to be particularly susceptible to brittle failure. At the same time, under all codes but one, the stress levels are held to quite conservative values; (17) finally, it is demonstrated that brittle failure results from a combination of many factors. There is no readily available material which would entirely prevent its occurrence, and there is no known test which will surely predict from the behavior of small specimens the performance of a given steel in circumstances where structural brittle failure might occur. In short, careful design, selection of materials, and good workmanship are of the greatest importance in the prevention of brittle failure in nonship structures. This is also true of ships.

Shevandin, Ye. M., et al., Concerning the Nature of the Scalar Effect in the Disintegration of Metals. (Doklady Akademii Nauk SSSR, 113, 5, pp. 1057-1060, 1957). 303

Sih, G.C., Paris, P.C., and Erdogan, F., Crack-Tip, Stress-Intensity Factors for Plane Extension and Plate Bending Problems. (ASME, Paper No. 61, APMW-29, 1961). 304

Abstract

A complex variable method for evaluating the strength of stress singularities at crack tips in plane problems and plate bending problems is derived. The results of these evaluations give Irwin's stress-intensity factors for plane problems and analogous quantities for bending problems, a form familiar to the practitioner of "fracture mechanics." The methods derived are integrated with the complex variable approach of Muskhelishvili to obtain the stress-intensity factors for various basic examples applicable to the extension and bending of plates with through-the-thickness cracks. The results suggest the possibility of extension of the Griffith-Irwin fracture theory to arbitrary plane extensional and/or bending problems in plates.

Smekal, Professor Adolf, The Nature of the Mechanical Strength of Glass. (Journal of the Society of Glass Technology, 20, p. 432, 1936). 305

Abstract

The fundamentals underlying the fracture of glass are explained on a theory of internal structural flaws. It is shown that rupture commences with a crack starting from a local fault, and is developed by secondary fracture surfaces originating at those places where the initial crack is extended by the natural inhomogeneities in the glass. The process of rupture is greatly influenced by the thermal agitation of the molecules.

Sneddon, J.N., Crack Problems in the Mathematical Theory of Elasticity. (North Carolina State College, Departments of Mathematics and Engineering Research, File No. ERD-126/1, Contract No. Nonr 486(06), May 15, 1961). 306

Soderberg, C. Richard, Mechanical Properties in Relation to Design Requirements. (Metallurgical Review, 1, 1, pp. 31-63, 1956). 307

Abstract

Perhaps the most important aspect of modern engineering in this respect is the acceptance of testing and research as indispensable adjuncts to design. The idea of laboratory and simulated-service tests on models and components, simple as it seems, has played an enormously important role in recent decades.

The considerations which guide the designer in his choice of material are many and varied. The present discussion, however, is deliberately confined to the phenomena of mechanical failure.

Spretnak, J.W. (The Ohio State University), A Summary of the Theory of Fracture in Metals. (Office of the Director of Defense Research and Engineering, DMIC Report 157, August 7, 1961, Defense Metals Information Center, Battelle Memorial Institute, Columbus 1, Ohio). 308

Abstract

The theoretical strength of metals, based on atomic forces, is in the order of 100 to 1000 greater than that observed. The various reasons for this discrepancy between theoretical and observed strength are discussed in detail, but the more important ones are (1) lattice imperfections, (2) the fact that real metals are polycrystalline aggregates, (3) crystalline anisotropy, and (4) the ability of metals to deform by shear.

Plastic flow, particularly heterogeneous plastic flow, is intimately associated with crack initiation. The precise conditions under which plastic flow ceases and bond rupturing (cracking) begins are not completely understood. The body-centered cubic lattice has geometric characteristics that make it particularly susceptible to fracture with little or no preceding plastic flow. Multidirectional stress fields, both microscopic and macroscopic, affect the degree of plastic deformation that precedes crack initiation. The theory of fracture as it exists today is reviewed. Though incomplete in many respects, it can be helpful in understanding the behavior of metal structures.

Stokes, R.J., Johnston, T.L., and Li, C.H., (Minneapolis-Honeywell Research Center, Hopkins, Minnesota), Crack Formation in Magnesium Oxide Single Crystals. (Philosophical Magazine, 3, pp. 718-725, 1958). 309

Abstract

Experimental evidence is presented which lends direct support to the Stroh mechanism for crack formation. After a magnesium oxide crystal was compressed about 3%, it was observed that minute cracks had been formed in the region of a kink band generated by non-homogeneous plastic strain. These cracks lay on conjugate (110) slip planes and not on the usual (100) cleavage planes. They extended in the form of (001) direction slits running right through the crystal.

Stokes, R.J., Johnston, T.L., and Li, C.H., The Relationship Between Plastic Flow and the Fracture Mechanism in Magnesium Oxide Single Crystals. (Fourth Technical Report, Office of Naval Research Project Nonr-2456(00) NR 032-451, February, 1959, Honeywell Research Center, Hopkins, Minnesota). 310

Abstract

Magnesium oxide crystals plastically deformed under a three point load develop internal slits coplanar with the (110) slip plane and parallel to the (001) bending axis in the tension region. Using etch pit techniques it has been shown that the slits lie along the edge of a (110) slip band and are confined between two adjacent orthogonal ($1\bar{1}0$) slip bands.

It is proposed that under certain circumstances edge dislocations moving in one of the ($1\bar{1}0$) slip planes pile into the barrier provided by a wider (110) slip band, and coalesce to form a slit nucleus along the line of intersection. This nucleus lies parallel to the (110) plane and grows by cleavage over this plane until it meets another ($1\bar{1}0$) slip band where it becomes halted. Thus cracks can be nucleated where clip bands intersect but, more important, they can also be stabilized by slip bands.

If microcracks form in the early stages of plastic flow their growth is unrestricted and the material is brittle. If the crystal is first plastically deformed to introduce sufficient slip the growth of the microcracks is impeded in certain directions and they develop into narrow slits. The material is then able to deform even further. The correlation between crystal ductility and the appearance of the fracture surface is consistent with this interpretation. For brittle specimens fracture starts from a point, whereas for ductile specimens the fracture appears to start from one of the narrow slits.

Stokes, R.J., Johnston, T L., and Li, C.H., Kinking and the Fracture of Ionic Solids. (Twelfth Technical Report, Office of Naval Research, Project Nonr-2456(00) NR-032-451, June, 1961). 311

Abstract

A single crystal undergoing plastic bending develops constraints due to the gradient in lateral contraction across the beam. These constraints result in lateral stresses which may be relieved by the process of anticlastic kinking. Anticlastic kink boundaries in rock-salt structure solids consist of arrays of $\langle 110 \rangle \{121\}$ edge dislocations formed by the interaction of two systems of $\langle 110 \rangle \{110\}$ glide dislocations, one system being responsible for slip in the main part of the crystal beam, the other confined to its corner.

Temperature affects the structure of kink boundaries and their subsequent role in initiating fracture.

1. At high temperatures ($\sim$0.3Tm). The resultant edge dislocations in the boundary can move over their $\{121\}$ slip planes and the kinks become sharp. The resultant dislocations are ineffective barriers to slip and the crystals are ductile.

II. At low temperatures ($\sim$0.1 - 0.2 Tm). The resultant edge dislocations are immobile and the kinks consist of a diffuse array. The resultant dislocations provide strong barriers to slip and cracks nucleate at the kink boundary.

III. At very low temperatures ($\sim$0.1 Tm). Fracture occurs before the second set of $\langle 110 \rangle \{110\}$ glide dislocations have been activated to generate anticlastic kinks. Relaxation of the lateral stress results in a complex fracture.

Compatible observations of the change in fracture behavior under bending over different temperature ranges have been made on a number of ionic solids.

Stroh, A.N., Brittle Fracture and Yielding. (Philosophical Magazine, 46, pp. 968-972, 1955). 312

Abstract

The stresses round a piled-up group of dislocations may either initiate a crack or operate a Frank-Read source by pulling it from its locking impurities; the latter is related to the propagation of a Lüders band. This interpretation leads to results in accord with experiment. The model gives a sharp transition from brittle to ductile behaviour as the temperature is increased.

Stroh, A.N., The Clevage of Metal Single Crystals. (Philosophical Magazine 3, p. 597, 1958). 313

Abstract

A model of cleavage applicable to metals cleaving on the slip plane is developed in which a crack is initiated at the end of a low angle tilt boundary terminating inside the crystal. The strength of the metal is determined by the difficulty of growth of the crack. Satisfactory agreement is obtained with the experimental results for zinc.

Stroh, A.N., The Formation of Cracks as a Result of Plastic Flow. (Proceedings Royal Society, 232A, p. 548, 1955). 314

Abstract

The stresses round a piled-up group of dislocations are investigated with reference to the initiation of a crack. A crack should form when

the group consists of about 1000 dislocations piled up under a stress of the magnitude occurring in a cold-worked metal. The stress system due to the crack is obtained. The crack will have a stable equilibrium length, but this length is likely to be determined by the amount of plastic flow which takes place round the tip of the crack.

Stroh, A.N., A Theory of the Fracture of Metals. (Advances in Physics, 6, p. 418, 1957). 315

Abstract

The topics which will be considered here can broadly be described as the transcrystalline fracture of polycrystalline materials; an attempt will be made to show how the principal features observed follow from a simple model. Single crystalls will not be considered in detail; though they have been the subject of some recent experimental studies, it has not yet proved possible to give a satisfactory account of their properties. Other forms of fracture, for example, fatigue, fracture under creep conditions, will also be excluded.

Taylor, Nelson W., Mechanism of Fracture of Glass and Similar Brittle Solids. (Journal of Applied Physics, 18, pp. 943-955, November, 1947). 316

Abstract

A theory is proposed which connects the stress, f, required to break a brittle material in simple tension, with its duration of application, t. The slow process preceding fracture is shown to be the orientation of the atomic network contained in an elementary prism of length

$$r = \lambda_0 E/f,$$

where E is Young's modulus and λ_0 is the critical elongation required for fracture. The rate-controlling factor is the activation energy, $E\alpha/f$, for the orientation or rearrangement of the atomic network under the stress, f. Moisture on glass, and moisture plus oxygen on certain metals, are important catalytic or fatigue-promoting factors because they reduce the unit activation energy, α. The theory leads to the equations

$$t = (1/k_0)e^{E\alpha/fkT}$$

and

$$\log t = \log k_0 + (E\alpha/2.3kT)/f,$$

where t is the time for fracture (duration of the stress), k is the Boltzmann constant, T the absolute temperature, and α and k_o are experimentally determined constants. The logarithmic expression has the same form as the Glathart-Preston (J. App. Phys. 17, 189, 1946) empirical relation logt = a/m + 1/fm, which, in the case of glass, appears to be valid over a time factor of 10^7.

The theory shows why a solid object does not have a single characteristic breaking strength, and how it adjusts its fracture mechanism to whatever stress is applied. Quantitative tests of the theory are made, using fracture data on various glasses and on one glass at various temperatures. Applicability of the theory to certain aspects of fatigue of metals under stress-corrosion conditions, as well as to failure by fracture of the more rigid organic plastics, is indicated.

An equation, $E\lambda_o = 2\gamma$, is proposed which connects Young's modulus and the critical fracture distance with the surface tension, γ, of the solid. Some examples are given.

Thomas, T. Y., Plastic Flow and Fracture in Solids. (Journal of Mathematics and Mechanics, 7, 3, p. 291, 1958). 317

Abstract

Basic concepts and main results. In this investigation we shall be concerned with an ideal solid possessing the following properties. First, the dynamical behavior of the solid can be described by the ordinary or linear theory of elasticity for stresses satisfying the condition $\sigma^*_{ij}\ \sigma^*_{ij} < K$ where K is a material constant and the quantities σ^*_{ij} ar the components of the stress deviator. Second, the solid has a sharply defined yield point given by the quadratic yield condition

$$\sigma^*_{ij}\ \sigma^*_{ij} = K. \qquad (1.1)$$

More explicitly, we understand by this latter requirement that when the stress condition (1.1) is satisfied the solid will enter the plastic state which, in this article, we shall assume to be governed by the ordinary form of the Prandtl-Reuss equations, namely

$$\frac{d\sigma^*_{ij}}{dt} = 2\mu(\epsilon_{ij} - \psi\sigma^*_{ij}),$$

in which μ is the usual elastic constant, ϵ_{ij} are the components of the rate of strain tensor and the quantity ψ is defined by

$$\psi = \frac{\epsilon_{ab}\,\sigma^*_{ab}}{K}.$$

Triplett, W. B., and Wells, C., Energy of Crack Formation and Crack Propagation under Impact. (Carnegie Institute of Technology, Metals Research Laboratory, Pittsburgh, Pennsylvania, Progress Report No. 1, October 15, 1958, Aeronautical Research Laboratory, Contract No. AF 33(616)-5830, Project No. 7021, Task No. 70627). 318

Abstract

A basic study of the relative energies of crack formation and crack propagation under impact loading has been started. The method used for making estimates of crack formation and crack propagation transition curves from impact transition curves is thought to be reliable and to have a wide application not only to body centered cubic metals and alloys but also to some face centered and hexagonal close packed materials. Evidence supporting this point of view is given. The statistical nature of impact properties has been discussed and evidence offered to support present opinion that determined impact transition curves are made up essentially of two normal probability curves, one a crack formation and the other a crack propagation transition curve. Each such curve is adequately described by two statistics. Relations between tensile strength, in the range 100,000 and 300,000 psi, and each of the variables, crack initiation (CI), crack propagation (CP), and total impact energy (CI + CP) are given. A literature survey of papers covering the subject of fracturing in metals and alloys has been completed.

Triplett, W. B., and Wells, C., Energy of Crack Formation and Crack Propagation under Impact. (Carnegie Institute of Technology, Metals Research Laboratory, Pittsburgh, Pennsylvania, Progress Report No. 2, January 15, 1959, Aeronautical Research Laboratory, Contract No. AF 33(616)-5830, Project No. 7021, Task No. 70627). 319

Abstract

The basic study of the relative energies of crack formation and crack propagation under impact loading was continued. Considerable evidence has been accumulated recently to show that the procedure developed and used in the present research program for making estimates of crack formation and crack propagation curves from impact transition curves is reliable, since comparable estimated and determined crack formation and crack propagation energies for specimens tested in the range 212 to -200° F. agree within the limits of experimental error. A

low energy blow technique was used for determining crack formation energies. The material recently studied includes two AISI steels, one a 4330 and the other a 43B40, together with a Ni-Cr and a Ni-Cr-Mo-T steel. Tentatively, a distinction has been made between cracks and tears, and a discussion has been given of various aspects of the crack and tear phenomena. Maximum bending and permanent set information suggests that most of the energy involved in bending the V-notch Charpy specimens used in this investigation sufficiently to cause the formation of cracks under impact loading is elastic rather than plastic energy.

Triplett, W.B., and Wells, C., Energy of Crack Formation and Crack Propagation under Impact. (Carnegie Institute of Technology, Metals Research Laboratory, Pittsburgh, Pennsylvania, Progress Report No. 3, April 15, 1959, Aeronautical Research Laboratory, Contract No. AF 33(616)-5830, Project No. 7021, Task No. 70627). 320

Abstract

As a result of this basic study of the relative energies of crack formation and crack propagation under impact loading, crack formation and crack propagation transition curves have been estimated for five steels. These include two AISI steels, the first a 4340, the second a 4330, and three others, one a Ni-Cr, the second an AISI 8740, and the third an AISI 87B40 to which rare earth metals had been added. Estimated and determined crack formation energies agree within 1 ft-lb which is well within the limits of experimental error. Crack formation energies for each of the materials investigated were determined from low energy blow impact data for specimens tested at several temperatures in the range 212 to -200° F. Crack formation, crack propagation to fracture and overall impact energies are about twice as large for longitudinal as for transverse specimens coming from the AISI 4340 steel quenched and tempered to a tensile strength of about 200,000 psi. Based on results obtained for the Ni-Cr steel, two curves have been drawn, one to represent the relation between crack formation energy and testing temperature, and the other to represent the relation between tear formation energy and testing temperature. Addition of boron and rare earth metals to the AISI 8740 had little effect on crack formation energy but increased crack propagation energy to fracture significantly. Part of this increase is attributed to the effect of rare earth metals on the amount and nature of nonmetallic inclusions present in the steel. It appears from present results that impact quality of steels is improved by vacuum melting and vacuum pouring, when the quality, without such treatment, is less than a certain threshold value, at and above which specimens fail by tearing.

Triplett, W.B., and Well, C., Energy of Crack Formation and Crack Propagation under Impact. (Carnegie Institute of Technology, Metals Research Laboratory, Pittsburgh, Pennsylvania, Progress Report No. 4, on Contract No. AF 33(616)-5830, July 15, 1959, to Wright Air Development Center (WCLJL) Air Research and Development Command, United States Air Force, Wright-Patterson Air Force Base, Ohio). 321

Abstract

Progress made up to the beginning of April, 1959, was described in quarterly reports written on this contract (1, 2, 3). Results in these reports show that (a) the procedure developed and used for estimating crack formation and crack propagation transition curves from determined impact versus temperature of testing curves (1), and (b) an experimental technique developed by others (4. 5) and used for making determinations of crack formation energies (2) gave reliable data (3) and have a wide application, not only to body-centered cubic metals and alloys, but also to some face-centered and hexagonal close-packed material as well (1).

Longitudinal and transverse impact transition curves for a typical AISI 4340 steel quenched and tempered to a tensile strength of about 200,000 psi were obtained, and estimates were made of crack formation and crack propagation transition curves for this product (3). Comparable information was secured for four other steels: one, AISI 4330; two Ni-Cr; three, AISI 8740; and four, AISI 87B40 to which rare earths had been added (3).

During the three-month period, April 1 through June 30, 1959, additional information pertaining to the present study of the energy of crack formation and crack propagation under impact loading was accumulated using AISI 4340 steels from three typical heats. Two other steels were used: one designated HY80 and containing Ni, Cr, Mo, and one designated T-1 containing Ni, Cr, Mo together with Cu, V, and B.

Wachtman, Jr., J.B., Factors Controlling Resistance to Deformation and Mechanical Failure in Polycrystalline (Glass-Free) Ceramics. (National Bureau of Standards Report, NBS Project 0901-11-4416, NBS Report 5128, Progress Report No. 24, Contract No. AF 33(616)-56-4, NBS File No. 9.1/1115-C, for the period October 1, 1956 to January 1, 1957). 322

Abstract

Ceramic bodies, in comparison with metals, are characteristically brittle at room temperature. However, ceramic oxide single crystals begin to deform plastically at about one-half their absolute melting temperature and at higher temperatures become quite easily deformable. The objective of this project is to determine the temperature and stress necessary to cause plastic deformation of polycrystalline (glass-free) ceramic oxides and to study the dependence of strain on time, stress, and temperature. It is hoped to interpret these data in terms of factors controlling deformation such as structure, grain size, and impurities.

Creep tests of high-purity large grain-size polycrystalline alumina in the temperature range 1100° to 1200° C. gave a total time dependent strain of only about 2×10^{-5} in 25 hours.

Internal friction measurements on polycrystalline alumina indicate that the internal friction is a maximum at about 1250°C. for a frequency of 2,139 cycles/sec.

Washburn, J., Gorum, A.E., and Parker, E.R., Cause of Cleavage Fractures in Ductile Materials. (Transactions AIME, 215, p. 230, 1959). 323

Abstract

Experimental evidence was obtained in support of the idea that cleavage fracture can be initiated by dislocation pile-up. The high ductility of MgO crystals when tested in bending compared to their relative brittleness in tension was explained on the basis that large pile-ups are more likely in a tension specimen.

Weibull, W., Investigations into Strength Properties of Brittle Materials. (Ingeniorsvetenskapsakademiens, Handlingar NR p. 149, 1938). 324

Abstract

By measuring that force which is required to produce cracks in a glass plate subjected to the pressure of steel balls of various diameters, it was found that the ultimate strength to a high degree depends on the rate of application of load, and that the relation between the breaking load and the rate of load application may be expressed by a linear extrapolation formula. It is furthermore shown that if the glass plate is contiguous to certain electrolytes, the ultimate strength may in some cases increase

more than 100 percent. Finally, an experimental verification is given of a law set up by Auerbach and stating that the ultimate strength is direct proportional to the ball radius, and not to the square of the ball radius, as required by the classical theory of strength.

An examination of the ultimate strength in the case of two-dimensional state of stress in glass and bakelite plates shows that the ultimate strength of these materials is in all probability determined by the maximum tensile stress, and not by the shearing stress or the shear strain energy.

Weil, N.A., Review of Brittle Fracture Criteria in Ceramic Materials. (Symposium (Brittle Behavior) Mat. Advisory Board, Division of Eng. and Ind. Research, National Academy of Sciences, National Research Council, Washington 25, D.C., Part 2, December, 1960). 325

Wells, A.A., Strain Energy Release Rates for Fractures Caused by Wedge Action. (Naval Research Laboratory, Mechanics Division, Washington, D.C., March, 1956). 326

Abstract

In the brittle fracture test devised by Robertson, a cleavage crack is made to run, in a plate under a low value of static tensile stress, by means of an impact wedging action produced within a shallow edge notch. Robertson found that cracks would not propagate for a given temperature below the crack arrest transition temperature in a particular steel, for static tensile stresses less than a certain value, which he considered to be a definite property of the material. However, in the variation of the test carried out at the Standard Oil Development Laboratory (S.O.D.) it was found that the critical value of this static stress could be increased by increasing the width of the specimen from 16 to 72 inches, or decreased by increasing the energy of the wedge blow.

It is shown in this report that, in such a test, the strain energy release rates from the wedge force and static stress may be combined so as to give a minimum when the crack has a given length. The minimum values so obtained for the S.O.D. test results correspond reasonably well with minimum surface energy values determined by independent experiment for similar steels and temperatures. In addition, it is shown that the applied tensile stresses to maintain a given strain energy release rate are decreased by decreasing the specimen width and increasing the wedging force by amounts which bear comparison with the S.O.D. test results. Thus the

suggestion is made that the Robertson and S. O. D. tests are controlled, at least below the transition temperature, by strain energy release rates.

Westergaard, H.M., Bearing Pressures and Cracks - Bearing Pressures through a Slightly Waved Surface or through a Nearly Flat Part of a Cylinder, and Related Problems of Cracks. (Journal of Applied Mechanics, 6(2): A-49-A-53, June, 1939). 327

Abstract

The task is undertaken of determining the bearing pressures, and the stresses and deformations created by them, in some cases that differ from those considered by Hertz in his classical study of contact. Thus two solids are examined which, before loading, are in contact along a row of evenly spaced lines in a horizontal plane, as indicated in Fig. 1(a). Between these lines the surfaces have a separation defined by a nearly flat cosine wave. A uniform pressure on top of the upper solid creates contact over an area consisting of a row of strips, reduces the separation of the solids between the strips, as suggested in Fig. 1(b), and creates contact pressures distributed as indicated in Fig. 1(c), with vertical rises in the diagram of pressure at the edges of the strips. At a greater load the width of the strip becomes equal to the wave length, and the contact is complete. At still greater loads the stresses increase as if the two solids were one. The procedure by which this problem is solved is demonstrated first by showing its easy application to some well-known cases, especially Hertz's problem of circular cylinders in contact.

Further applications are to a noncircular cylinder resting on a solid with a flat top, with an initial separation of the surfaces varying as the fourth power of the distance from the initial line of contact; to partial contact of two surfaces which are initially plane, except that one of them has a ridge or several parallel ridges; and to some related problems in which two parts of the same body are partially separated by the forming of one or more cracks.

Wirtz, K., The Relation of the Tensile Strength of Homogeneous Glass Rod to its Cross-section. (Journal of the Society of Glass Technology, 20, p. 65, 1936). 328

Abstract

The relation between tensile strength and cross-sectional area is given.

Zener, C., and Hollomon, Plastic Flow and Rupture of Metals. (Publication No. 9, A.S.M., 1943).

Abstract

This paper constitutes an attempt to co-ordinate and interpret the present knowledge of the plastic flow and rupture of metals. Certain of the data found in the literature required the introduction of new concepts for their explanation. New models have been suggested which appear to co-ordinate better the existing knowledge in this broad field.

Two systems have been in common use for specifying (a) the conditions for the initiation of plastic flow, (b) the precise nature of flow under a given stress pattern, (c) the relation between the strain hardening occurring in different types of flow. In this paper these two systems are discussed in detail, and a comparison is made between their predictions and the experimental observations. A new theoretical treatment is given of the application of these systems to the problem of strain hardening.

Almost insuperable difficulties prevent the direct determination of the relation between stress and strain at high rates of strain. An indirect method is proposed whereby this information may be easily obtained.

Inexplicable phenomena in metals have frequently been disposed of by the assumption of imperfections. In this paper many phenomena not previously understood are shown to be explicable in a qualitative manner by a single type of imperfection which may be quite precisely defined, namely by the concept of microscopic cracks. These phenomena include: the decrease in the rate of strain hardening in torsion at large strains compared with the strain hardening in tension, the elongation which accompanies large angles of twist, the effect of a prior twist upon the type of tensile fracture. A quantitative analysis, first suggested by Griffiths, is applied to these cracks. This analysis attempts a correlation of the fracture stress with the size of these micro cracks which are correlated with certain elements of the microstructure.

BRITTLE BEHAVIOR

ARMOUR RESEARCH FOUNDATION OF ILLINOIS INSTITUTE OF TECHNOLOGY

Anderegg, F.O., Strength of Glass Fiber. (Industrial Engineering Chemistry, 31, p. 290, 1939). 330

Abstract

The strength of glass is reduced by discontinuities but, by thorough melting and proper methods of attenuation, the effect is greatly reduced so that strengths of the order of 400,000 pounds per square inch are being produced commercially with fine fibers for textiles. Generally, the finer the fiber, the greater the strength, the discontinuities apparently being pulled out lengthwise. The strength may be summarized from the "bulk" strength plus corrections for the decreased cross section. The scatter in strength results of such a material as glass is considerable, resulting from the variations in the number and in severity of discontinuities. The shorter the fiber tested, the higher the average results. The breaking is also probably affected by thermal energies which vary from atom to atom. Glasses low in alkali or entirely free of it have extremely high electrical resistance and stand up well to repeated wetting and drying. On the other hand, glasses containing alkali seem to withstand most acids quite well. Fused silica has yielded strengths as high as 3,500,000 pounds per square inch.

Apelt, G., Effect of Rate of Loading and Torsional Deformation on the Tensile Strength of Glass Rods. (Zeitschrift Physik, 91, pp. 336-343, 1934). 331

Abstract

The ultimate strength was independent of the rate of loading at room temperature. At the temperature of liquid air, however, no such relationship held.

Bergstedt, P., Compilation of Materials Research Data, Second Summary Report - Phase II. (Report AE 62-0060-1, for the period September 1, 1961 to March 1, 1962, General Dynamics / Astronautics, San Diego, California, prepared for Aeronautical Systems Division, Wright-Patterson AFB, Ohio - Contract AF 33(616)-7984, Task No. 73812). 332

Abstract

This second summary report under Phase II of Contract AF 33(616)-7984 contains brief descriptions of materials research projects on

which work was in progress during the reporting period at General Dynamics/Astronautics, San Diego, California.

Campbell, J.E., Compilation of Tensile Properties of High-Strength Alloys. (DMIC Memorandum 150, April 23, 1962, Defense Metals Information Center, Battelle Memorial Institute, Columbus, Ohio). 333

Abstract

Representative properties are given for high-strength alloys of the common base metals having melting points from that of magnesium to that of tungsten.

The primary purpose is to illustrate the upper limits of the yield strength to density ratios for these alloys within the range of possible service temperatures.

No discrimination is made regarding fracture toughness (tendency to fracture in a ductile manner at service temperatures), stress-corrosion properties, necessity for protection from oxidation at elevated temperatures, fabricability, weldability, or machinability. However, these properties also must be considered in selecting materials for critical applications. Tensile properties are given for each of the alloys over as broad a temperature range as was feasible considering available data and potential service temperatures.

Coble, R.L., and Kingery, W.D., Effect of Porosity on Physical Properties of Sintered Alumina. (Journal of the American Ceramic Society, 39, 11, pp. 377-385, 1956). 334

Abstract

Porous structures having a continuous solid phase with isolated pores were prepared by the addition of different amounts of crushed naphthalene to an alumina casting slip. Samples of from 5 to 50% porosity were fired together for comparable grain development, eliminating structural variables except porosity. Effects of porosity and temperature on strength, elastic modulus, modulus of rigidity, and coefficient of thermal expansion were investigated. Effects of porosity on thermal stress resistance and torsional creep properties were studied at constant temperature.

Dent, Beryl M., The Effect of Boundary Distortion on the Surface Energy of a Crystal. (Philosophical Magazine, 8, p. 530, 1929). 335

Abstract

A method of evaluating the effect of surface distortion on the surface energy of polar crystals is described.

The results for eight monovalent alkaline halides are given, and show that the distortion decreases the surface energy by about 20 percent.

The effect is found to be due almost entirely to the polarization of the surface ions.

Drozdovskiy, B.A., and Fridman, Ya. B., Effect of Fractures on Mechanical Properties of Structural Steel. (Vliyaniye Treshohin Na Mekhanicheskiye Svoystva Konstruktsionnykh Staley, pp. 12-260, 1960. English Pages: 285). 336

Drucker, D.C., Mylonas, C., and Lianis, G., Exhaustion of Ductility of E-Steel in Tension Following Compressive Prestrain. (Welding Journal Research Supplement, March, 1960). 337

Abstract

Cylindrical bars of project E-steel were precompressed from 10 to 47%. Unnotched 0.505 tensile specimens were machined from the precompressed bars. Some were kept cold to prevent aging, some were aged under load, and some aged without load. All were tested at an ambient temperature of approximately 80° F.

The reduction of ductility which occured in most of the cases was appreciable. In three of the specimens it was spectacular. One of the three suffered a complete tensile fracture on a cross-sectional plane at a strain of less than 2%.

Duckworth, W.H., Precise Tensile Properties of Ceramic Bodies. (Journal of the American Ceramic Society, 34, No. 1, pp. 1-9, 1951). 338

Abstract

Factors in obtaining and interpreting tensile data on ceramic bodies are discussed, with particular attention given to the use of bending.

A bend test can be used conveniently to obtain precise tensile data as long as stress is directly proportional to strain in both tension and compression. The moduli of elasticity in tension and in compression need not be equal. To account for any such inequality, strain in both bottom and top longitudinal fibers should be considered in computing the tensile stress. Extraneous stresses in bending can be essentially eliminated through proper specimen design and manner of loading. Details for the consideration of extraneous stresses in practice are presented, along with an equation for computing tensile stress precisely from bend-test data. Limited experimental work on oxide-base and silicate-base bodies supported the theoretical analysis of bending and indicated the suitability of a refined bend test for precise ceramic work.

Duckworth, W.H., Johnston, J.K., Jackson, L.R., and Schofield, H.Z., Mechanical Properties of Ceramic Bodies. (Project Rand, USAF Project RR 1, R-209, The Rand Corporation, Santa Monica, California; Battelle Memorial Institute, Columbus, Ohio, August 31, 1950). 339

Abstract

As the first phase of a broad, fundamental program on the load-bearing characteristics of ceramic bodies, room-temperature compression, tension, and shear data were obtained on porous and nonporous specimens of a normal porcelain.

Stress was proportional to strain to failure in all instances, and moduli of elasticity in compression were slightly higher than corresponding moduli in tension. Moduli of rigidity were related to moduli of elasticity in accordance with the well-known relationship

$$G = \frac{E}{2(1+\nu)},$$

where ν = Poisson's ratio. Within the range of porosities used, from 0 to about 30 percent, the elastic properties were related to porosity very nearly as follows:

$$\frac{G}{G_o} = \frac{E}{E_o} = 1 - 2P,$$

where P = porosity expressed as a fraction, and subscript zero refers to the nonporous body. The ratios, E/E_o and G/G_o are expected to decrease less rapidly with further increases in porosity. For minimum-weight design based on elastic properties, the nonporous body should be used.

Strength phenomena could be correlated fairly well on the basis of Griffith's flaw theory. In this respect, compression specimens failed in shear at a recorded strength about eight times greater than the tensile strength, and there was evidence that the tensile strength could be expressed as

$$s_t = \frac{m}{C} = \frac{B\sqrt{E}}{C},$$

where m = molecular cohesion
C = factor expressing the stress-concentrating action of the most dangerous flaw
B = constant.

The critical flaws causing failure of porous specimens apparently resulted from the voids in the body rather than from flaws in the solid material. Strength-density ratios decreased with increasing porosity in accordance with these considerations. By proper selection and placement of pores, higher strength-density ratios at a given porosity could undoubtedly be obtained. At a porosity below about 30 percent, however, the strength-density ratio could not exceed that of the nonporous body because of the nature of the change in E with porosity.

Tensile stresses caused failure in the shear tests at recorded strengths of about one-half the strengths expected from tensile tests. The presence of biaxial stresses or directional properties might explain this apparent anomaly.

Ellis, G. C., The Ductility Problem of Reactor Beryllium. 340
(UKAEA Industrial Group Report 145 - RD/C, H.M. Stationery Office, Paper No. 10, p. 46, 1957).

Abstract

Brittleness in Metals. A conference held at R and D Branch Culcheth Laboratories, November 1, 1957.

Endell, K., Consolidation and Relieving from Tension, Softening, and Crystallization of Ceramic Products in Relation to Structure, Temperature, Time, and Formation. (Transactions-German Ceramics Society, 13-3, pp. 97-124, 1932). 341

Abstract

An attempt is made to present a brief review of the present state of our knowledge of the relation between viscosity and temperature in technical glasses, metals, and minerals.

Gerard, George, Structural Significance of Ductility in Aerospace Pressure Vessels. (ARS Journal, pp. 1216-1221, August, 1962). 342

Abstract

The results reported in this paper include an exploratory experimental study of small gage length fracture strains at stress concentrations and an analysis of the weakening and strengthening effects of stress concentrations in terms of a ductility ratio. The structural significance of tests used to evaluate ductility in the presence of stress concentrations are discussed, and a procedure to evaluate the ductility ratio as a basic material property is suggested. Finally, the structural strength/weight characteristics of various high strength sheet materials are discussed in terms of the structural design problems associated with aerospace pressure vessels.

Gorum, A.E., Luhman, W.J., and Pask, J.A., Effect of Impurities and Heat-Treatment on Ductility of MgO. (Journal of the American Ceramics Society, 43, p. 241, 1960). 343

Abstract

Stress-strain curves were obtained in flexure and in tension on single crystals of MgO. A decrease in iron content and high-temperature heating and rapid cooling caused a decrease in strength and increase in ductility. Heat-treatment of previously deformed specimens increased their strength. The slip band structures resulting from deformation were brought out by chemical etching, and their significant features are discussed.

Gorum, A.E., Parker, E.R., and Pask, J.A., Effect of Surface Conditions on Room-Temperature Ductility of Ionic Crystals. (Journal of the American Ceramics Society, 41, p. 161, 1958). 344

Abstract

With the progress on dislocation theories and a better understanding of flow phenomena, it was predicted that a class of materials normally

considered to be brittle, namely, ionic solids having cubic crystal structures, would possess a degree of ductility. Experimental results on a number of ionic materials indicate that face-centered cubic and body-centered cubic ionic materials can exhibit a considerable amount of ductility under controlled conditions. It was found that these materials are inherently ductile rather than brittle and that there appear to be two factors, a surface reaction with components of the air and impurity concentration, that exert control over the ductility. The examination of the air embrittlement indicated that oxygen and nitrogen are the cause of decreased ductility in water-soluble salts such as KCl and KBr. The effect on the surface can be inhibited by surface treatment or by immersion in oil. Other materials such as MgO and LiF do not seem to exhibit a surface embrittlement. MgO does, however, show a time-dependent ductility that is attributed to the presence of impurities.

Gurland, J., The Influence of Basic Design and Processing Variables on the Properties of Sintered WC-Co Alloys. (Division of Engineering, Brown University, Providence, Rhode, Island. Department of Army Project No. DA-599-01-004, Ordnance R and D Project No. TB2-0001, OOR Project No. 2060, Contract No. DA-19-020-ORD-4888, April, 1960). 345

Abstract

The characteristic properties of sintered carbides are accounted for by the nature of brittle fracture and the specific influences of volume, surface finish, loading rate, and grain size upon fracture strength are demonstrated by experimental results. The effects of mixing procedures and sintering conditions upon density, composition, and structure are evaluated on the basis of the liquid phase sintering mechanism. Also considered are compacting pressure, pressureless consolidation, infiltration, and paraffin addition as factors which influence the properties.

Gurney, C., Effect of Duration of Loading on the Strength of Glass. (Nature, 157, p. 662, 1946). 346

Abstract

Murgatroyd and Sykes report experiments in which they pre-stressed glass for a prolonged period at a stress thought to be sufficient ultimately to break it, and they afterwards broke the glass in a rapid loading test. They found that the pre-stressing had not significantly reduced the breaking stress in the latter test. Orowan had previously suggested that if the time effect on the strength of glass was due to the spread

of initial cracks as a consequence of atmospheric attack, the results of pre-stressing at a load sufficient ultimately to break the glass would be to reduce the strength under a subsequent short-time breaking test. Murgatroyd and Sykes therefore concluded that their results are incompatible with any theory which relates the decay in strength of glass to increase in length of cracks.

Orowan's deduction was based on the interpretation of Griffith's criterion of fracture, which regards crack-spreading at constant surface tension as contrary to the laws of thermodynamics below the Griffith load, but that it proceeds catastrophically as soon as the Griffith load is reached. In a paper I read to the British Rheologists Club in June last year, I showed that crack-spreading by Griffith's mechanism in a material of atomic constitution is not catastrophic at the Griffith load. This load is the smallest at which a crack may start to spread by this mechanism. The rate of spreading depends on the rate at which thermal motions overcome atomic energy barriers, which may be very slow even at loads exceeding Griffith's criterion. Catastrophic fracture will not occur until the crack has attained a length such that the strain energy in the material at its end combined with the average thermal motion is sufficient to overcome the average energy barrier. Orowan's prediction, therefore, needs re-examination.

Hahn, G. T., and Jaffee, R. I., A Comparison of the Brittle Behavior of Metallic and Nonmetallic Materials. (DMIC Memorandum 107, OTS PB 171626, Defense Metals Information Center, Battelle Memorial Institute, Columbus, Ohio, May 16, 1961). 347

Abstract

This presentation of properties serves to illustrate many similarities among metals and nonmetallics subject to brittle behavior. Elastic properties are comparable in many cases. Both metals and nonmetallics are capable of plastic deformation. In both instances, ductility and fracture behavior can depend on composition, microstructure, temperature, and other test conditions. Finally, neither group is immune to fatigue or thermal shock. Significant differences also exist. Ductility, notch sensitivity, and energy-absorption data suggest that nonmetallics are more susceptible to cracking and fracture than brittle metals.

Haward, R. N., Time Factors in the Breaking of Toughened Glass. (Nature, 157, p. 21, 1946). 348

Abstract

Recently there has been much interest in the relationship between rates of stressing and strength properties of glass, and several hypotheses and relations have been put forward in connexion with the quantitative phenomena concerned. In one of these, it is suggested that the decrease of the breaking stress with increase in duration of loading should be slower with toughened glass than with sheet. However, the same conclusion follows from the quantitative formulation of the commonly accepted view of the nature of toughened glass, namely, bending strength of toughened glass = bending strength of sheet glass + increase due to toughening process = $f_{(t)} + K$.

Hodgdon, F.B., Stuart, D.A., and Bjorklund, F.E., The Application of Rate-Process Theory to Glass. I. Breaking Strength. (Journal of Applied Physics, 21, pp. 1156-1159, November, 1950). 349

Abstract

An equation relating the ultimate strength of glass and porcelain to time under load is derived using the rate-process theory of Eyring. The data of Preston and co-workers are used to calculate the constants in the equation. The agreement between theoretical and experimental results is excellent.

Holland, A.J., and Turner, W.E.S., The Effect of Sustained Loading on the Breaking Strength of Sheet Glass. (Journal of the Society of Glass Technology, 24, p. 46, 1940). 350

Abstract

The effect of sustained loading on the modulus of rupture of specimens of sheet glass having round and well-polished edges and of dimensions 10 x 0.8 x 0.275 cm. has been determined by loading the specimens to the extent of 100, 90, 80, 70, 60, 50, 40, and 30 percent of the previously determined mean breaking load and measuring the time interval between loading and fracture. For loads equal to or greater than 70 percent a number of specimens fractured before the full load was reached. For loads less than 70 percent some of the specimens remained unbroken after 1000 hours, the number unbroken increasing as the load decreased until all the specimens remained unbroken after 1000 hours at the 30 percent load. For those specimens fracturing it was found that a straight-line relationship held between the logarithm of the mean breaking time and the logarithm of the applied stress. A factor of safety of not less than four was suggested for sheet glass of the type described.

ARMOUR RESEARCH FOUNDATION OF ILLINOIS INSTITUTE OF TECHNOLOGY

Holms, Arthur G., and Repko, Andrew J., Correlation of Tensile Strength, Tensile Ductility, and Notch Tensile Strength with the Strength of Rotating Disks of Several Designs in the Range of Low and Intermediate Ductility. (Technical Note 2791, National Advisory Committee for Aeronautics, 1952). 351

Abstract

Burst tests were conducted on several designs of sound disks and disks with defects. Results were compared with tensile strength, tensile ductility, and notch tensile strength. The purposes of the investigation were to determine the extent to which disk strength can be increased by increasing tensile strength, to investigate the extent to which a correlation exists between disk strength and several mechanical properties of materials at low ductilities, and to present some data on the influence of several types of stress concentration on the strengths of disks made from ductile and brittle materials.

For the brittle materials (that may have been subject to chemical segregations) the disk strength did not correlate with tensile strength. For these low-ductility materials (elongation equal to or less than 4.0 percent) and for ductile materials for which notch strength data were available, the disk strength was found to correlate better with the combination of tensile strength and notch strength ratio than with the combination of tensile strength and elongation. For disks possessing much sharper stress raisers (defects), the notch tensile strength was superior to the conventional tensile strength as a basis for correlating disk strength with mechanical properties of the sound material.

In general, experimentally determined disk strengths for ductile materials were slightly less than values predicted from tensile strength values by the concept of average stress. In the case of brittle materials, the observed values were significantly less than the predicted values. The rule that the strength reduction in disks due to holes is approximately equal to the percentage of diametral cross-sectional area removed by the holes was substantiated for disks of ductile materials having large central holes and moderate size eccentric holes. The rule was not substantiated for disks of ductile materials having small central holes and the rule was not substantiated for disks made from materials of low ductility.

Hulse, Charles O., and Pask, Joseph A., Mechanical Properties of Magnesia Single Crystals in Compression. (Journal of the American Ceramics Society, 43, p. 373, 1960). 352

Abstract

Stress-strain curves of single crystals of magnesia compressed in the (100) direction are reported at temperatures from - 196° to 1200° C.;

curves are also shown for different rates of loading at room temperature. The crystals show considerable ductility at all temperatures and at room temperature can be deformed plastically about 6% before fracture at stresses which are about one-quarter of reported polycrystalline fracture strengths. The macroscopic yield drops apparently exponentially from an extrapolated value of 50,000 pounds per square inch at absolute zero to about 4500 pounds per square inch at temperatures of 900° C. and higher. Heat-treatment has an appreciable effect on the yield stress. The resistance of the material to deformation increases with the number of slip systems and bands activated because of the barriers to dislocation movements which occur at slip band intersections. At about 2 to 3% strain, stress concentrations begin to be relieved by small internal cracks which are not easily propagated. This effect is extensive before final macroscopic failure of the crystal occurs. Preliminary creep test above the macroscopic yield stress and in the temperature range 800° to 1000° C. show large instantaneous plastic deformations followed by slow constant-rate creep.

Jacobsen, R.H., and Durelli, A.J., The Brittle Material Method of Experimental Stress Analysis and Failure Problems in Brittle Materials. (Armour Research Foundation of Illinois Institute of Technology, Project No. 90-812D, Venture No. 1791Q, Contract No. DA 11-022-ORD-10, Frankford Arsenal, Philadelphia, Pennsylvania, Final Report - December 29, 1950). 353

Abstract

This report deals with fundamental research in the development and application of the brittle material method of experimental stress analysis.

The authors studied the influence of thirteen variables on the ultimate strength of the brittle material. They include physical variables and processing variables, loading conditions and stress conditions. Among the conclusions given in the report are the following: (a) Specimens taken from the bottom portion of a casting have greater densities and strength than specimens from the top of a casting. (b) The rate at which a load is applied to the brittle material has no influence on its strength. (c) If a specimen is stressed nearly to failure a number of times, its strength will be increased. (d) If a near failure load is maintained on a specimen for a period of time, its strength will be increased. (e) The strength of a specimen is inversely related to the volume of material under high stress in the specimen. (f) The strength is directly related to the stress gradient, other things remaining constant.

Three applications of the method which have been conducted at Armour Research Foundation are described, and it is shown that the method can be used efficiently in practical applications.

ARMOUR RESEARCH FOUNDATION OF ILLINOIS INSTITUTE OF TECHNOLOGY

Jaffe, R. I., Maykuth, D.J., Refractory Materials. (DMIC Memorandum 44, OTS PB 161194, Defense Metals Information Center, Battelle Memorial Institute, Columbus, Ohio, February 26, 1960). 354

Abstract

Subjects of interest to the structural application of refractory materials include availability, extraction, consolidation, fabrication, stability, mechanical behavior at low and high temperatures, and physical properties important in thermal stress.

Kelsey, R.A., Strength of Welded Panels of 2014 and 2219 Sheet as Determined by Tension and Bulge Tests. (Alcoa Research Laboratories, Report 12-61-37, June, 1961). 355

Abstract

Tensile tests were made on wide, slotted sheet specimens of welded 2014 and 2219 alloy, heat treated, and aged after welding. The results were compared with the results of tensile tests on wide and narrow specimens, both plain and welded, without slots, and with the results of bulge tests made on plain and welded specimens from the same lot of material.

Kick, F., (A.E.R.E. Harwell, April, 1956, BW, HD2186). Contributions to the Knowledge of the Mechanics of Brittle Materials. (Dingler's Polytechnical Journal, 247, 1, pp. 1-5, 1883). 356

Knudsen, F.P., Dependence of Mechanical Strength of Brittle Polycrystalline Specimens on Porosity and Grain Size. (Journal of the American Ceramics Society, 42, 8, pp. 376-387, 1959). 357

Abstract

An empirical equation form, approximating the apparent dependence of the strength of brittle polycrystalline specimens on the combined effect of porosity and grain size, has been developed from concepts and data in the literature. The form is shown to be applicable to data for thoria and chromium carbide specimens.

Knudsen, F.P., Effect of Porosity on Young's Modulus of Alumina. (Journal of the American Ceramic Society, 45, 2, pp. 94-95, 1962). 358

Abstract

Presents a graphic compilation of available data on the Young's moduli of porous polycrystalline alumina at room temperature. The compiled moduli and corresponding porosities have been plotted semilogarithmically in accordance with the general equation form proposed by Spriggs.

$$E = E_o e^{-bP}$$

E = Young's modulus of a porous polycrystalline body.
E_o = Young's modulus of a nonporous polycrystalline body.
e = The Napierian number, 2.71828.
b = An empirical constant.
P = Fractional pore volume of body.

Kropschot, R.H., and Mikesell, R.P., Strength and Fatigue of Glass at Very Low Temperature. (Journal of Applied Physics, 28, 5, p. 610, 1957). 359

Abstract

The low temperature strength of glass, defined in terms of the stress required to cause fracture, has been discussed by Onnes and Braak, Smekal, and Vonnegut and Glathart. At room temperature and below, the strength of glass for a given load duration increases with decrease in temperature. The fatigue of glass, defined as the decrease in breaking stress with increased duration of load, decreases with decreasing temperature, but still exists at liquid nitrogen temperature.

The purpose of this investigation was to supplement the existing information on the strength properties of glass and to extend these studies to lower temperatures and longer fatigue times. This information was obtained to assist in the design of windows for cryogenic devices such as liquid hydrogen and liquid helium bubble chambers. The work was undertaken at the request of the University of California Radiation Laboratory.

Tests were made on BSC-2 (Corning 8370) optical glass in the abraded and unabraded condition. Simple beams with two-point loading were tested at 20° K, 76° K, 194° K, and 296°K. The rate of stress increase (800, 10, and 1 psi/sec) has very little effect at the two lower temperatures but is important at the two higher temperatures. The results also show that the breaking stress at 20° K is nearly the same as at 76°K. Some fatigue was found to exist at liquid nitrogen temperature (76°K); however, the endurance limit appears to be greater than 9000 psi compared to

approximately 5000 psi or less at room temperature. The modulus of elasticity changes by less than 2% over the entire temperature range investigated.

Lang, S.M., Properties of High-Temperature Ceramics and Cermets - Elasticity and Density at Room Temperature. (National Bureau of Standards Monograph 6, March 1, 1960). 360

Abstract

In order to provide some of the basic data necessary for the effective utilization of ceramics and cermets in various high-temperature applications, a specimen "bank" of such materials, mainly commercially fabricated, was established for the measurement of physical properties and constants. This Monograph describes: (1) The materials and some of their fabrication data; (2) bulk densities; (3) theoretical densities; and (4) the dynamic room-temperature elastic constants. Data are given for 46 sets of specimens, representing 20 different materials; these include oxides, carbides, borides, cermets, and an intermetallic compound. A statistical evaluation was used for analyzing the data.

Results of the room-temperature measurements show that: (1) Significant variations are common both in the specimens of one group and from group to group of specimens prepared of the same material; (2) the largest variations occur for specimens formed by hot-pressing, although average values are higher for hot-pressed specimens; and (3) measurements of the dynamic elastic constants by the sonic method are more sensitive as indicators of homogeneity and group uniformity than bulk-density measurements.

Lang, S.M., and Knudsen, F.P., Some Physical Properties of High-Density Thorium Dioxide. (Journal of American Ceramic Society, 39, p. 415, 1956). 361

Abstract

The values for a number of physical properties are reported for a very high density form of thorium dioxide. When specimens of a mixture of 99 1/2% ThO_2 and 1/2% CaO, by weight, were hydrostatically pressed at 30,000 pounds per square inch and heat-treated for one hour at 1800° C., they attained 99.0% of theoretical density. All the test specimens were extremely brittle. Physical-property values determined at room temperature were the following: lattice constant; bulk and theoretical (X-ray) densities; compressive and impact strengths; Knoop hardness; modulus of rupture and Young's modulus, determined by a static method; Young's modulus and the shear modulus, determined by a dynamic method; Poisson's ratio and

the bulk modulus, calculated from the dynamic-test data; and the velocity of sound through the material. The properites determined at elevated temperatures were the following: linear thermal expansion; modulus of rupture and Young's modulus, determined by a static method; Young's modulus and the shear modulus, determined by a dynamic method; and Poisson's ratio, calculated from the elevated-temperature dynamic-test data. "Martin's diameter" grain counts were taken for the material both before and after heat-treatment.

Machlin, Dr. E.S., Status Report on Nonmetallic Fibrous Reinforced Metal Composites. (Materials Research Corporation, Contract NOw 61-0209-c, Bureau of Naval Weapons, Department of the Navy, 1961). 362

Abstract

The literature on fibers and fiber reinforced composites has been reviewed and evaluated. It is concluded that, in principle, nonmetallic fiber reinforced metals can have the largest strength/weight and modulus/weight ratios of all known materials, exceeding the values of those presently available by many factors, particularly at elevated temperatures. In practice, realization of the potential has been frustrated by two factors.

1. Thermal degradation of fiber strengths.
2. Inadequate fabrication procedures.

The inadequacies of fabrication techniques employed to date have been considered in detail and the requirements for an adequate fabrication technique have been listed.

The problems requiring solution have been listed and a level of research to solve these problems has been recommended.

MacKenzie, J.K., The Elastic Constants of a Solid Containing Spherical Holes. (Proceedings Physics Society, London, 63B, No. 1, pp. 2-11, 1950). 363

Abstract

The effective bulk and shear moduli are calculated by a self-consistent method due to Fröhlich and Sack. The bulk modulus k is determined by applying a hydrostatic pressure, and the shear modulus μ by applying a simple homogeneous shear stress, to a large sphere. Each hole is surrounded by a spherical shell of real material, and the reaction of the rest of the material is estimated by replacing it by equivalent

homogeneous material. For consistency, both the density and the displacement of the outer spherical boundary must be the same whether the hole and its surrounding shell are replaced by equivalent material or not. The effective elastic constants calculated from these conditions are

$$1/k = 1/k_0\rho + 3(1-\rho)/4\mu_0\rho + O\left[(1-\rho)^3\right],$$

$$(\mu_0 - \mu)/\mu_0 = 5(1-\rho)(3k_0 + 4\mu_0)/(9k_0 + 8\mu_0) + O\left[(1-\rho)^2\right]$$

where k_0 and μ_0 refer to the real material and ρ is the density of the actual material relative to that of the real material; in the next approximation k depends on the standard deviation of the volume of the holes.

The dilatation due to a distribution of pressures in the holes is

$$\bar{p}(1/k - 1/k_0),$$

where $\bar{p}$ is the mean obtained when the pressure in each hole has a weight proportional to the volume of the hole. By using the hydrodynamic analogue of the elastic problem, the theory is briefly applied to the theory of sintering, and used to discuss the effective viscosity of a liquid containing small air bubbles.

Maxwell, W.A., Properties of Certain Intermetallics as Related to Elevated-Temperature Applications. I - Molybdenum Disilicide. (National Advisory Committee for Aeronautics, Research Memorandum - E9G01, October 14, 1953). 364

Milligan, Lowell H., Note on Modulus of Rupture of Cylindrical Ceramic Rods when Tested on a Short Span. (Journal of the American Ceramic Society, 36, pp. 159-160, 1953). 365

Abstract

It is known that for rectangular bars corrections are necessary for the simple modulus of rupture formula to obtain true cross-bending strengths when the ratio of span to bar depth is less than about 10 : 1. The experiments described in this note develop empirical data on this subject for cylindrical rods of low span-to-diameter ratios.

Murray, G. T., Brittle-Ductile Transition Temperatures in Ionic Crystals. (Journal of the American Ceramic Society, 43, p. 330, 1960). 366

Abstract

The strain at fracture as measured in bending NaCl, LiF, and MgO has been shown to be markedly temperature dependent. Air aging, substructure, and grain boundaries act to elevate the transition temperature of NaCl. Aging in air increases the transition temperature of MgO, and this embrittlement can be removed by high-temperature annealing followed by air quenching.

National Research Council, Refractory Inorganic Nonmetallic Structural Materials. Report of the AD HOC Committee of the Materials Advisory Board - No. MAB-169-M, Contract DA 36-039-SC-76436, Division of Engineering and Industrial Research, National Academy of Sciences, Washington, D.C., January, 1961). 367

Abstract

Structural materials are and will be required for use at temperatures of 1650C (3000F) and above in missile and space-vehicle motor and leading-edge applications. While a few metals, notably W, Ta, and Mo retain strength above this temperature, they suffer from a serious lack of oxidation resistance. At these high service temperatures the nonmetallic refractory structural materials retain strength and phase stability but have a tendency toward brittle fracture at lower temperatures. The nonmetallic inorganic structural materials include primarily refractory compounds in the forms of borides, beryllides, carbides, nitrides, silicides, oxides, and elemental carbon in the form of graphite.

Prime weapons systems contractors have complained often about the inability of the ceramic industry to provide new materials, complete property data, and rapid delivery service for new applications which are poorly defined in terms of environments and specific materials requirements. Inorganic nonmetallic structural materials which may be used in future high temperature military applications, with the exception of graphite, currently represent a small percentage of the special refractories business. Special refractories sales are less than $20,000,000 per year and cannot support the research and development needed to make fully engineered new structural materials available to the Defense Department. The Committee believes that if adequate support is provided, useful new materials can be made available to answer many of the problems encountered in the materials barrier.

National Research Council, Summary Reports of the Steering Committee and the Review Committees, Vol. 1. (Department of Defense Program on Materials Research and Development, Division of Engineering and Industrial Research, National Academy of Sciences, Washington, D.C., December 31, 1961). 368

Obreimoff, J.W., The Splitting Strength of Mica. (Proceedings Royal Society, London, A, 127, p. 290, 1930). 369

Abstract

In the present work it will be shown that the splitting strength is a constant for mica; that we can determine a surface energy of mica which is independent of the shape of the mica sheets chosen and that mica placed in optical contact is totally restored. A description will also be given of some electrical phenomena obtained by splitting mica in a high vacuum.

Orowan, E., On the Plasticity of Crystals. I. (Zeitschrift Physik, 89, pp. 605-659, 1934). 370

Palmour, III, Hayne, Kriegel, W.W., DuPlessis, J.J., and Harrell, G.O., Selected Abstracts on the Mechanical Behavior of Ceramics. (Bulletin No. 73, July, 1959, Department of Engineering Research, North Carolina State College, Raleigh, North Carolina. 371

Parker, Earl R., Pask, J.A., Washburn, J., Gorum, A.E., and Luhman, W., Ductile Ceramics - A High Temperature Possibility. (Journal of Metals, 10-5, pp. 351-353, 1958). 372

Abstract

Investigations of mechanical properties of some ionic materials has shown the effect of surface conditions on room-temperature ductility. Cubic ceramic crystals possess substantial amounts of ductility at room temperature. Even the refractory ceramic material, MgO can be elongated as much as 20 percent on the tension of a single crystal bend-test specimen.

Purity and environmental effects play a major role in brittleness. There seems to be little or no reason to doubt that some ductile polycrystalline ceramic materials will be forthcoming within the next few years.

Pearl, Harry A., Nowak, John M., and Deban, Harry G., Mechanical Properties of Selected Alloys at Elevated Temperatures. Part II, Design Criteria of Silicon Carbide. (Wright Air Development Division, WADC Technical Report 59-702, Part II, March, 1960). 373

Abstract

A study was made of nondestructively testing silicon carbide by density and density uniformity, dynamic modulus by sonic technique, X-ray diffraction under transverse load, electrical resistivity, and internal friction. Dynamic modulus of silicon carbide was experimentally determined at 80 F and 2200 F. Modulus of rupture tests were conducted at 80 F, 2200F, and 2400 F.

The variability of the properties of the silicon carbide and the lack of simple correlations between the properties and geometry require the use of a statistical approach to correlate mechanical properties and geometry. A theoretical analysis is presented on the effect of specimen size, surface finish, and methods of loading on the strength properties of silicon carbide.

Available literature and manufacturers' property data for various types and forms of commercially available silicon carbide are tabulated. Various areas of possible application of silicon carbide in aircraft and missiles and design parameters for leading edge applications are given.

Preston, F. W., The Time Factor in the Testing of Glassware. (Journal of the American Ceramic Society, 18, p. 220, 1935). 374

Abstract

A preliminary report on the effect of the time element on the apparent strength of glass is given. Tests have been run on bottle glass from three seconds to 30 minutes duration and on polished plate and drawn window glass (in the form of laths) from five seconds to several hours.

Republic Aviation Corporation, Compilation of Unpublished Materials Information. (RAC 357-5, ARD 767-256, March 31, 1962, Second Semi-Annual Report, Contract AF33(616)-8084, November, 1961 through March, 1962). 375

Abstract

Summaries are presented covering some of the many materials programs being conducted at the Republic Aviation Corporation. These programs are conducted under company sponsorship and in support of contractual commitments. The summaries reflect the scope of Republic's nonproprietary materials research on metallics and special purpose materials in the areas of fundamental research, applied research and development, engineering evaluation, processing development, and testing techniques. The programs described herein vary in complexity from a sophisticated study of fracture phenomena to a routine evaluation of crazing in acrylics. Each summary describes the objective and current progress of the materials programs reported.

Ryshkewitch, Eugene, Rigidity Modulus of Some Pure Oxide Bodies. (Journal of the American Ceramic Society, 34, p. 322, 1951). 376

Abstract

Rigidity modulus of several sintered pure oxides was measured using specially prepared test pieces. A particular form of samples permitted an exact measurement of their dimensions and insured their proper elastic torsion deformation under a given load. Sintered alumina was tested up to 1550°C. Monocrystalline corundum, sintered stabilized zirconia, sintered pure beryllia, thoria, spinel, and zircon were tested at room temperature. Close agreement was noted between rigidity modulus values and Young's modulus values.

Samsonov, G.V., and Umanskiy, Ya. S., Hard Compounds of Refractory Metals. (NASA TTF-102, June, 1962. Translation of "Tverdyye Soyedineniya Tugoplavkikh Metallov." Published by the State Scientific-Technical Literature Publishing House, Moscow, 1957). 377

Abstract

The book describes the properties, methods of production, and areas of use of the hydrides, carbides, nitrides, borides, and silicides of

the refractory transition metals of groups IV, V, VI, VII, and VIII, of D. I. Mendeleev's periodic system (titanium, zirconium, vanadium, niobium, tantalum, molybdenum, tungsten, iron, etc.), as well as their alloys, which have great significance both in the metallurgy of special alloys, and in the technology of producing hard alloys.

The book is designed for engineering-technical workers and workers of the scientific research institutes of the metallurgy industry.

Samsonov, G.V., Neshpor, V.S., and Khrenova, L.M., Hardness and Brittleness of Metal-Like Compounds. (Physics of Metals and Metal Science, Vol. 8, No. 4, October, 1959. Publishing Office Metallurgizdat Sverdlovsk, pp. 595-598; 622-630). 378

Abstract

The microhardness of a number of metal-like compounds of transition metals was investigated at various loads. It was established that the microhardness numbers depend on the load at which the investigation is carried out.

The dependence between the microhardness numbers and the load is the same for materials with very high and comparatively low hardness; it is apparently determined by the nature of the plastic deformation of the surface of the solids during microhardness testing.

The brittleness of metal-like compounds was investigated by the microbrittleness method. The brittleness indices obtained in the present study are in a satisfactory agreement with the brittleness indices which we had earlier established for some compounds.

The brittleness of the compounds increases with the decrease in the mean-square displacements of the centers of the molecular complexes in the crystal lattices of the compounds, i.e., with an increase in the strength of the interatomic bond and a decrease in the possibility for stress relaxation in the material.

The hardness of metal-like compounds increases in the sequence silicide-nitride-carbide-boride, whereas the brittleness increases in the sequence silicide-boride-nitride-carbide.

Sandven, O.A., Cermets as Potential Materials for High-Temperature Service. (Report No. 99, North Atlantic Treaty Organization, Advisory Group for Aeronautical Research and Development, April, 1957). 379

Abstract

The high-temperature strength of cermet materials is generally superior to the conventional high-temperature constructional materials. Their oxidation resistance can also be increased to a very high level, but their lack of ductility makes them unfit for constructional use.

Relatively few cermet systems have been properly investigated, and it may be possible to overcome the lack of impact strength by using new Hard Metal-Binder Metal combinations, or by better production methods.

If it is possible to increase the impact strength to a moderate value without the loss of creep resistance and oxidation resistance, the cermets will make excellent materials for high-temperature purposes.

Smallman, R.E., Ductile-Brittle Transition in Non-Ferrous B.C.C. Metals. (UKAEA Industrial Group Report 145-RD/C. H.M. Stationery Office, Paper No. 8, pp. 41-43 - A Conference on Brittleness in Metals held at R. and D Branch Culcheth Laboratories, November 1, 1957). 380

Abstract

The phenomenon of brittle fracture in iron is well known and its practical importance has led to widespread investigation extending over several years. Investigation of the other b.c.c. metals has not been so widespread but their growing importance necessitates a more detailed examination. This paper briefly reviews the existing work on these metals.

Spaderna, Conan H., Some Aspects of Bending Brittle Materials. (Experimental Mechanics, pp. 71-72, August, 1961). 381

Abstract

Information of value to design engineers faced with problem of recommending materials for applications involving bending is presented in this technical note.

Spinner, Sam, Elastic Moduli of Glasses at Elevated Temperatures by a Dynamic Method. (Journal of the American Ceramic Society, 39-3, pp. 113-118, 1956). 382

Abstract

The elastic constants of thirteen glasses were measured by a dynamic method at elevated temperatures. Both Young's modulus and the shear modulus were determined and from these Poisson's ratio was calculated as a function of temperature. Fused silica, Vycor-brand glass, and Pyrex-brand glass had positive temperature coefficients of elastic moduli, whereas all the other glasses showed negative coefficients. Poisson's ratio was found to rise with temperature in all thirteen glasses. This is interpreted as an indication of an approach to the liquid state.

Spriggs, R.M., and Brissette, L.A., Expressions for Shear Modulus and Poisson's Ratio of Porous Refractory Oxides. (Journal of the American Ceramic Society, 45, 4, pp. 198-199, 1962). 383

Abstract

A previous note suggested that the elastic modulus (E) of polycrystalline ceramic oxide materials, particularly of aluminum oxide, was exponentially dependent on porosity. In a similar study, the shear modulus (G) of poly crystalline alumina has been found to follow the same type of relation. The effect of porosity on Poisson's ratio, calculated from the exponential relations given herein and previously for the shear and elastic moduli, is also shown for one set of data.

The expression for the effect of porosity on shear modulus is of the type

$$G = G_o e^{-bP}$$

G = shear modulus of porous polycrystalline specimen.
G_o = shear modulus of nonporous polycrystalline specimen.
e^o = the Napierian number, 2.71828...
b = an empirical constant
P = volume fraction porosity = $\frac{\text{void volume}}{\text{total specimen volume}}$

Stokes, R.J., Johnston, T.L., and Li, C.H., Effect of Surface Condition on the Initiation of Plastic Flow in Magnesium Oxide. (Third Technical Report, Honeywell Research Center, Hopkins, Minnesota, Office of Naval Research, Project NOnr-2456(00) NR-039-041, September, 1958). 384

Abstract

Dislocation half-loops, artificially introduced by sprinkling with carborundum, were subjected to stress using three-point loading. The different stages of loop expansion and multiplication were then correlated with the macroscopic stress-deflection curve. Loop expansion started at approximately 1/3 rd. of the "yield stress", defined here as the motivation stress. Above 1/2 of the "yield stress" simple multiplication commenced while about 2/3 rds. of the yield stress gross multiplication developed short slip line segments. These values were not affected by the age of surfaces exposed to both dry and wet air.

Slip was not detected on unsprinkled crystals below 2/3 rds. of the yield stress. Thus the stress to activate intrinsic sources, defined here as the activation stress, was approximately twice the motivation stress. This relationship was independent of the strain rate used.

It is concluded that lattice resistance takes the form of a viscous drag rather than a static type of force.

Uzhik, G. V., Resistance of Plastic Metals to Brittle Disintegration. (Contributions of the Academy of Sciences, USSR, pp. 685-687, January 5, 1954. Technical Documents Liaison Office unedited Rough Draft Translation). 335

Weyl, W. A., The Mechanical Strength of Glass. (The Glass Industry, 27, 1, January, 1946). 336

Abstract

Part II deals with some features of the strength of glass which seemed both puzzling and unique: (1) the shape factor, (2) the time factor, (3) the role of the environment, (4) the influence of the temperature, (5) the influence of the previous heat treatment.

Part III - Fundamentals concerning the tensile strength of glass: (1) the molecular process of fracture, (2) tensile strength, a "structure sensitive" property, (3) the role of flaws, (4) the influence of temperature on the tensile strength, (5) the influence of the duration of the load on the strength value, (6) the influence of the environment on the strength of glass, (7) the influence of a surface layer prestressed under compression.

Part IV - Formulation of a basis for comparing the strength of glass with that of other materials; (1) the tensile strength of glass as compared with that of organic polymers, (2) the "fatigue" of glass as compared with other "Chemical Fatigue" phenomena, (3) the tensile strength of glass as compared with the fatigue strength of metals, (4) the tensile strength of

"toughened" glass as compared with the fatigue of metals prestressed under compression.

Part V - Possibilities of increasing the strength of matter by prestressing the surface under compression. Part VI - The "anomalous" strength of glass fibers. Part VII - The hardness of glass. VIII - Summary and conclusions.

Wygant, James F., Elastic and Flow Properties of Dense, Pure Oxide Refractories. (Journal of the American Ceramic Society, 34, 12, pp. 374-380, 1951). 387

Abstract

Mechanical properties, including creep rates, were measured for slip-cast magnesia, hydrostatically pressed magnesia, thoria, zircon, and mullite. None equaled alumina or zirconia in strength, rigidity, or creep resistance. Although mullite was found to have good properties, magnesia showed the best properties of the oxides tested. Thoria was very weak, zircon was highly plastic above 1000° C. Elastic and flow properties were determined primarily by the crystal structure and atomic bonding of the oxides and secondarily by grain boundary conditions.

Zener, C., and Hollomon, J. H., Effect of Strain Rate upon Plastic Flow of Steel. (Journal of Applied Physics, 15, pp. 22-32, 1944). 388

Abstract

An experiment has been designed to check a previously proposed equivalence of the effects of changes in strain rate and in temperature upon the stress-strain relation in metals. It is found that this equivalence is valid for the typical steels investigated. The behavior of these steels at very high rates of deformation may, therefore, be obtained by tests at moderate rates of deformation performed at low temperatures. The results of such tests are described. Aside from changing the isothermal stress-strain relation, an increase of strain rate tends to change the conditions from isothermal to adiabatic. It is found that at low temperatures, the adiabatic stress-strain relation in the plastic range is radically different from the isothermal, having an initial negative rather than a positive slope. This initial negative slope renders unstable homogeneous plastic deformation.

THERMAL STRESS

ARMOUR RESEARCH FOUNDATION OF ILLINOIS INSTITUTE OF TECHNOLOGY

Achard, Robert, High Temperature Composite Structure. (Engineering Report No. 12317, Martin Company Space Systems Division, Baltimore, Maryland. Contract AF 33(616)-7497, Project No. 1368, Task No. 13719, April, 1962). 389

Abstract

The objectives of this program are the design, development, fabrication, test, and evaluation of a nose cone heat shield capable of efficient operation with surface temperatures in the range of 3000° to 4000° F. This component will be a representative structural element complete with details suitable for efficient structural use on hyperthermantic vehicles.

The results of the 16-inch prototype panel tests were analyzed. Supplementary tests were conducted to improve the design of the above panel. Based upon these and additional tests, two final panels were designed.

Anthony, Frank M., and Mistretta, Andrew L., Investigation of Feasibility of Utilizing Available Heat Resistant Materials for Hypersonic Leading Edge Applications. Volume VIII, Tests of Molybdenum and Graphite Leading Edge Components. (WADC Technical Report 59-744, Bell Aerosystems Company, June, 1961. Contract No. AF 33(616)-6034, Project No. 7350, Flight Dynamics Laboratory Project No. 1368, Aeronautical Systems Division, Air Force Systems Command, United States Air Force, Wright-Patterson Air Force Base, Ohio). 390

Abstract

The purpose of this contract was to investigate the feasibility of utilizing available heat resistant materials in the fabrication of leading edges for hypersonic gliders. This particular volume presents the results of tests conducted on the molybdenum alloy and graphite leading edge assemblies which were developed.

Each design was subjected to five elevated temperature exposures, in still air, which simulated spatial and time-wise variations of temperatures expected during flights of global range. Induction heating was employed for the molybdenum design and quartz lamp radiant heating was used for the graphite design. In addition, thermal strain measurements were obtained for each design during exposures of reduced severity, and the graphite design was loaded statically to destruction at room temperature.

Both designs performed satisfactorily from a strength point of view. Thermal stresses resulting from the variations in heat input caused

no structural failures. However, oxidation failures occurred in both the W-2 coating on the molybdenum alloy and in the siliconized coating on the graphite. Data measured during the various tests compared well with analytical expectations.

Anthony, Frank M., and Pearl, Harry A., Investigation of Feasibility of Utilizing Available Heat Resistant Materials for Hypersonic Leading Edge Applications, Volume III - Screening Test Results and Selection of Materials. (WADS Technical Report 59-744, Bell Aircraft Corporation, Materials Laboratory, Contract No. AF 33(616)-6034, Project No. 7350, July, 1960, Aircraft Laboratory Project No. 1368, Wright Air Development Center, Air Research and Development Command, United States Air Force, Wright-Patterson Air Force Base, Ohio). 391

Abstract

The purpose of this contract was to investigate the feasibility of utilizing available heat resistant materials in the fabrication of leading edges for hypersonic boost-glide vehicles. This particular volume presents the results of the preliminary portion of the material evaluation portion of the program. Material requirements were established for this specific application. In order to assess the suitability of a given material, knowledge of many material characteristics is required. Of primary importance are oxidation resistance, high thermal emissivity, high thermal conductivity, low thermal expansion, reproducible strength characteristics, and fabricability. Other characteristics which must be considered are specific heat, modulus of elasticity, erosion characteristics, and density. Over 100 technical reports were reviewed, and approximately 50 suppliers and fabricators were contacted to obtain data on materials which might be suitable for leading edge applications at 2500°F. to 3000°F. A total of 106 materials were considered including 22 refractory metals, 30 protective coatings, and 54 refractory non-metals.

From the review of available materials it was apparent that much of the information required for assessing suitability was lacking. A screening test program was initiated, therefore, to fill the gaps in available data and to provide consistent sets of data upon which to base intelligent selections. The methods used in choosing the materials to be screened considered availability and the complex interrelation among design and material parameters. From the 106 candidate materials three metals, five coating systems, and seven non-metals were subjected to screening tests. Determination of oxidation resistance, thermal emissivity, thermal conductivity, thermal expansion, mechanical strength, and modulus of elasticity, were made from room temperature to 2700°F.

Using the data obtained experimentally and the methods developed for assessing suitability, the .5% titanium alloy of molybdenum, Chromalloy W-2 coating, Durak MG coating, and siliconized ATJ graphite were found to be the most promising materials for the specific application. Consequently these materials were selected for further evaluation.

Clarke, F.J.P., Miles, G.D., and Sambell, R.A.J., Basic Mechanisms Leading to Fracture by Thermal Shock. (AERE - R 3877, Metallurgy Division, U.K.A.E.A. Research Group, Atomic Energy Research Establishment, Harwell. HL 61/5664-C.14, November, 1961). 392

Abstract

Crystals and hot-pressed bars of magnesium oxide have been thermally shocked at various heat transfer levels. The shock is characterized in terms of the plastic strain it should produce. Theoretical and experimental values of strain show satisfactory agreement and it is established that this is not appreciably affected by heat transfer time from 20 μsecs to several seconds. The effects of thermal shock on crack propagation in single crystals, bicrystals, and hot-pressed polycrystalline magnesia are described and discussed.

Cotterell, B., and Parkes, E.W., Thermal Buckling of Circular Plates. (Reports and Memoranda No. 3245, H.M.S.O., London, 1962). 393

Abstract

The post-buckling behaviour of a circular plate is investigated for two conditions - heating over the centre and heating at the edge. In the former case the plate buckles into the form of a saucer; in the latter into a saddle shape. The plate may be free or it may be subjected to a variety of edge restraints. For centre heating, edge restraint has little effect on the behaviour; for edge heating it is extremely important.

General non-dimensional curves are presented for the deflected form and bending stresses. Experiments carried out on plates under centre heating generally support the analyses, but precise confirmation was impossible owing to inherent experimental difficulties.

Dioguardo, P.R., and Lloyd, R.D., Investigation of the Effects of Rapid Loading and Elevated Temperatures on the Mechanical 394

Properties of Compressive and Column Members. (Technical Documentary Report No. ASD TR 61-499, January, 1962. Directorate of Materials and Processes, Aeronautical Systems Division, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, Project No. 0(7-7381), Task No. 73812, Prepared under Contract No. AF 33(616)-7345, by the Marquardt Corporation, Van Nuys, California).

Abstract

The short time tensile and compressive properties were evaluated for Rene' 41 and Haynes 25 sheet alloys at room temperature and 800° to 2200° F. Tests conducted at various strain rates (0.00001 to 0.1 in /in. /sec.) produced significant differences in strength, particularly at elevated temperatures.

Creep properties, both tensile and compressive, were determined for the same alloys at temperatures of 1600° to 2200° F. and times up to 15 minutes. At the higher stress levels, creep rates became very rapid and considerable amounts of plastic strain occurred in times of 1 second or less.

A preliminary study was conducted on the use of programmed, forced strain rate tests to predict short time creep properties.

Fitzsimmons, E.S., Thermal Diffusivity of Refractory Oxides. 395
(Journal of American Ceramic Society, 33, 11, pp. 327-32, 1950).

Abstract

A method of measuring the thermal diffusivity of refractory materials is described. The experimental procedure is based on transient heat conditions requiring the measurement of only the time interval and the change in temperature. The results obtained for alumina, magnesia, zirconia, and alumina-clay specimens show the variation of diffusivity with temperature. A comparison of the results with those of previous studies is given.

Glenny, E., and Taylor, T.A., Mechanical Strength and Thermal Fatigue Characteristics of Silicon Nitride. (Memorandum No. M 351, U.D.C. No. 546.281.17:539.319, National Gas Turbine Establishment, November, 1961). 396

Abstract

The mechanical properties, and the thermal shock and thermal fatigue characteristics of three reaction-sintered (density 1.9 to 2.6 g/ml) and one hot-pressed (density 3.00 to 3.18 g/ml) silicon nitride showed significant differences according to composition and method of manufacture. The resistance to creep (at 1000° C. to 1200°C.) and to thermal fatigue, particularly of the dense grades, can be considerably superior to that of creep-resistant alloys. However, the appreciable variation in performance of all grades indicates that further development of the manufacturing technique is necessary to produce consistent behaviour.

Gurney, C., and Pearson S., The Effect of the Surrounding Atmosphere on the Delayed Fracture of Glass. (Proceedings of the Physical Society, Section B., Vol. 62, Part 8, No. 356B, p. 469, August, 1, 1949). 397

Abstract

Round soda-lime-silica glass rods were subjected to a series of given bending moments, and times to fracture were recorded. Experiments were made in air and in vacuo of 10^{-1} and 10^{-5} mm. of mercury; and the effects of heating in vacuo to drive off absorbed atmospheric constituents were also investigated. For the same prior heat treatment the slopes of the curves of stress against time to fracture decrease with decrease of pressure. At 10^{-5} mm. Hg., after heat treatment, the curve was very flat. It is evident that the main cause of delayed fracture is attack of the glass by atmospheric constituents. Experiments in which glass was subjected to air from which water vapour and carbon dioxide were removed separately and together showed that both these substances cause delayed fracture. Other constituents of the atmosphere seem relatively ineffective. These conclusions are in agreement with the work of Preston and his collaborators. It is further concluded that the atmospheric constituents can be supplied by capillary liquid contained in surface cracks and by migration from surface layers as well as by direct attack from the gaseous phase.

Kerper, Matthew, Diller, C.C., and Eimer, E.H., Properties of Glasses at Elevated Temperatures. (National Bureau of Standards, WADC Technical Report 56-645, Part II, ASTIA Document No. 204212, November, 1958, Wright Air Development Center). 398

Abstract

The modulus of rupture and the modulus of elasticity have been determined at several temperatures on a soda-lime-silica glass and a

borosilicate glass that are commercially available in the form of plate glass. Stress-rupture and creep results for the annealed soda-lime-silica glass are presented. The results of some studies on the effect of temperature, cutting, and sandblasting on the modulus of rupture are presented.

Kingery, W.D., Factors Affecting Thermal Stress Resistance of Ceramic Materials. (Journal of the American Ceramic Society, 38, 1, pp. 3-15, 1955). 399

Abstract

The sources and calculation of thermal stresses are considered, together with the factors involved in thermal stress resistance factors. Properties affecting thermal stress resistance of ceramics are reviewed, and testing methods are considered.

Kingery, W.D., Thermal Conductivity: XII, Temperature Dependence of Conductivity for Single-Phase Ceramics, (Journal of the American Ceramic Society, 38, 7, pp. 223-256, 1955). 400

Abstract

Theoretical relationships and experimental data concerning thermal conductivity for a number of oxide materials have been compared over a wide temperature range. Deviations from the basic proportionality between k and 1/T are caused by radiant-energy transmission, a high Debye temperature, a low mean free path of the thermoelastic waves, porosity, and in a few cases electronic conductivity. Extrapolation of thermal conductivity data to high temperatures is not reliable.

Kingery, W.D., and Pappis, J., Note on Failure of Ceramic Materials at Elevated Temperatures under Impact Loading. (Journal of the American Ceramic Society, 39, p. 64, 1956). 401

Abstract

The failure of Al_2O_5, MgO, Pyrex-brand glass, soda-lime-silica soft glass, and a triaxial semivitreous whiteware body under impact loading has been observed in some cases from room temperature to 1600°C. The pendulum energy required to fracture these materials remains constant or decreases with temperature over the temperature region of possible use.

Kunen, Alfred E., Hartwig, Frederick J., and Bressman, Joseph R., Tensile Properties of a Sillimanite Refractory at Elevated Temperatures. (National Advisory Committee for Aeronautics, Technical Note No. 1165, November, 1946). 402

Abstract

The tensile strength, the stress-to-rupture characteristics, and the modulus of elasticity of a sillimanite refractory were investigated at various temperatures. The tensile strength varied from a minimum of 8000 pounds per square inch at a temperature of 500° F. to a maximum of 19,000 pounds per square inch at 1800° F. The strength at 1950° F. was approximately 15,000 pounds per square inch. Heat-treating the tensile specimens for one-half hour at 1800° F. increased the tensile strength 35 percent at room temperature and 70 percent at 500° F. No increase in strength was noted at or above 1400° F.

At a temperature of 1600°F. the 100-hour rupture strength was 9600 pounds per square inch and the 1000-hour rupture strength was 8500 pounds per square inch. At 1800°F., the material withstood a stress of 6700 pounds per square inch for 19 hours.

The modulus of elasticity, which was determined only at room temperature, was 20.3×10^6 pounds per square inch and the material was elastic to the point of fracture.

The density of the sillimanite refractory was 0.10 pound per cubic inch or approximately one-third that of high-temperature metal alloys.

Lea, Professor F.C., The Effect of Low and High Temperatures on Materials. (Proceedings of the Institute of Mechanical Engineering, 1053, December, 1924). 403

Abstract

The results of the tests on materials at high temperatures, subjected to repetition stresses, show that very many millions of rapidly repeated stresses of magnitudes far greater than the creep stress can be applied without risk of fracture. These results throw important light on the possibility of materials healing after slipping, and indicate that viscosity plays an important part in the behaviour of materials subject to rapid repetitions of stress at high temperatures. If the fluctuations of stress are small and the stress is always in one direction the conditions approximate more and more to the statical condition; and further, if the time of application in one direction is not very small, the time factor becomes of great importance, and failure may occur. The full significance of the repeated stresses must be left, however, for a future communication.

MacGregor, C. W. and Welch, L. E., True Stress-strain Relations at High Temperatures by the Two-load Method. (Transactions of AIME, 154, pp. 423-437, 1943). 404

Abstract

It may be concluded from the data submitted that: (1) the two-load method can be used in the short-time high-temperature test provided appreciable creep does not occur during the test; (2) the true stress-strain curves are linear from the maximum load point to incipient fracture; (3) the effect of testing temperature on the true stress at the maximum load and on the average true stress at fracture is different for most of the materials tested (summarized in Table 2); (4) the ductility of metals at high temperature may best be pictured by the true uniform and true local necking strains upon which the testing temperature usually has a different effect, as revealed in Table 2; (5) that, while the testing temperature affects the true uniform and fracture strains differently, the true fracture and local necking strains are affected by temperature in a similar manner.

Majors, Jr., Harry, Thermal Shock and Fatigue, A Literature Survey. (Technical Report No. 1, Office of Ordnance Research, Project No. 1230, Contract No. DA-01-009-ORD-454, September, 1956). 405

Abstract

A literature survey is presented which includes (1) a comparison of brittle with ductile materials; (2) analytical analysis for thermal shock parameters (surface stresses-sudden cooling, temperature ratios when surface stress is maximum, and center stresses due to sudden heating); (3) experimental data on thermal shock; (4) Weibull's statistical theory applied to thermal shock; (5) a summary of work on thermal shock; (6) ductile materials under thermal shock; (7) descriptions of apparatus for determining basic data on thermal cycling; and (8) current studies on thermal cycling.

Manson, S. S., Behavior of Materials under Conditions of Thermal Stress. (N.A.C.A. Report 1170, Lewis Flight Propulsion Laboratory, Cleveland, Ohio, 1954). 406

Abstract

A review is presented of available information on the behavior of brittle and ductile materials under conditions of thermal stress and thermal shock. For brittle materials, a simple formula relating physical properties to thermal-shock resistance is derived and used to determine the

relative significance of two indices currently in use for rating materials. The importance of simulating operating conditions in thermal-shock testing is deduced from the formula and is experimentally illustrated by showing that BeO could be either inferior or superior to Al_2O_3 in thermal shock, depending on the testing conditions. For ductile materials, thermal-shock resistance depends upon the complex interrelation among several metallurgical variables which seriously affect strength and ductility. These variables are briefly discussed and illustrated from literature sources. The importance of simulating operating conditions in tests for rating ductile materials is especially to be emphasized because of the importance of testing conditions in metallurgy. A number of practical methods that have been used to minimize the deleterious effects of thermal stress and thermal shock are outlined.

Manson, S.S., and Smith, R.W., Theory of Thermal Shock Resistance of Brittle Materials Based on Weibull's Statistical Theory of Strength. (Journal of the American Ceramic Society, pp. 18-27, January, 1955). 407

Abstract

Present theories predicting the resistance of brittle materials to thermal shock are based on the premise that failure occurs on the attainment of a definite critical stress. However, the failure of many brittle materials has been shown to be dependent upon stress distribution within the body rather than upon the maximum stress criteria. Weibull's statistical theory of strength which accounts for this behavior is adapted to predict the strength of the circular disks of brittle materials subjected to peripheral thermal shock. This analysis shows, for those materials in which tensile strength differs appreciably from the bending strength, that considerable error can be introduced by the use of the conventional maximum stress theory of fracture when predicting thermal shock resistance over a wide range of quenching severities. Experimental thermal shock data for steatite are analyzed to show procedures for applying the theory.

Maxwell, W.A., Some Stress-Rupture and Creep Properties of Molybdenum Disilicide in the Range 1600° to 2000° F. (Research Memorandum - NACA RM-E52D09, National Advisory Committee for Aeronautics, Lewis Flight Propulsion Laboratory, June 24, 1952). 408

Abstract

An investigation of the stress-rupture and creep properties of hot-pressed molybdenum disilicide has produced the following results:

1. The stress-rupture properties can be summarized as follows:

Temperature (°F)	Stress (psi)	Time to rupture (hr)	Creep rate (in./in./hr)
1600	35,000	107	0.000024
1800	20,000	224	.000028
1900	12,000	110	.00073
2000	10,000	85	.0018

2. The use of molybdenum disilicide above 1800° F. may be limited by the creep rate rather than by the stress-rupture life.

3. The long-time strength of molybdenum disilicide at high temperatures is superior to that of the high-temperature alloys and titanium carbide ceramals.

4. A comparatively convenient and satisfactory method for creep and stress-rupture testing to 2000° F. has been developed.

Maxwell, W.A., and Smith, R.W., Thermal Shock Resistance and High-Temperature Strength of a Molybdenum Disilicide - Aluminum Oxide Ceramic. (Research Memorandum E53F26, National Advisory Committee for Aeronatuics, Washington, D.C., October 1; 1953). 409

Abstract

A ceramic consisting nominally of 75 percent molybdenum disilicide and 25 percent aluminum oxide was investigated to determine its thermal shock characteristics and high-temperature strength properties.

In a rim-quench thermal shock evaluation, the material was found to be superior to pure molybdenum disilicide. In a simulated altitude blow-out test, the material withstood an average of 2 1/2 cycles when quenched from 1800° F. The modulus-of-rupture strengths varied from 25,100 pounds per square inch at 1800° F. to 12,000 pounds per square inch at 2200° F.

McClelland, J.D., and Riley, W.C., Ceramics for up to 2100 deg C. (Space Aeronatics, pp. 111, 112, April, 1962). 410

Abstract

The urgent need for high-temperature aerospace materials is spurring on the development of new ceramics as well as the improvement of existing ones and of application methods. For temperatures around

1500 deg C., tantalum beryllide is an attractive newcomer, while from 1600 to 2000 deg c. the borides have great potential. Nitrides and silicides also show considerable promise. Typical of the improvement of existing materials is the recent production of translucent alumina and beryllia and of various types of carbides with melting points above 3000 deg C.

Because of their brittleness, present ceramics are best applied with higher compressive than tensile loads. However, ductile ceramics have already been produced in the lab and become available as structural materials in the reasonably near future.

Poulos, N.E., Elkins, S.R., and Walton, J.D., High Temperature Ceramic Structures. (Quarterly Report No. 23, Project No. A212, Engineering Experiment Station, Georgia Institute of Technology, February-April, 1962). 411

Abstract

The effort during this quarter was directed toward three phases of work: organic silicate impregnating, radome fabricating, and arc-plasma flame glazing. The major effort was expended in radome material evaluation and radome fabrication from slip-cast fused silica.

Preston, James B., and Kattus, J. Robert, Determination of the Mechanical Properties of Aircraft-Structural Materials at Very High Temperatures After Rapid Heating. (Southern Research Institute, WADC Technical Report 57-649, Part II, April, 1960, Materials Center Contract No. AF 33(616)-3494, Project No. 2998 Wright Air Development Division, Air Research and Development Command, United States Air Force, Wright-Patterson Air Force Base, Ohio). 412

Abstract

Structural components in high-speed aircraft and in missiles must function for short periods of time at high temperatures and at high stresses, and frequently the heating and loading occur simultaneously. The requirement for reliability without overdesign demands accurate test data obtained under conditions approximating the expected operating conditions. In an effort to fulfill a portion of this need, this program was divided into four independent areas of work as follows: (1) The tensile properties of unalloyed beryllium were determined at test temperatures from ambient through 1500° F. (2) The short-time, elevated-temperature tensile properties were determined for ten combinations of base materials

and coating materials (Cr-Ni electroplate on copper sheet, Rokide A on copper sheet, Rokide Z on copper sheet, Rokide ZS on copper sheet, Cr electroplate on A-nickel sheet, Ni-Cr electroplate on molybdenum sheet, Rokide Z on molded graphite, Rokide ZS on molded graphite, Crystalon C on molded graphite, and SiC-SiN on molded graphite). (3) The effects of linear thermal gradients up to 1500° F./in. on the tensile properties of a typical refractory alloy were investigated. (4) The effects of simultaneous heating and loading on the tensile properties of a typical structural alloy were investigated. This report covers the first three of these four areas of work; a supplementary report will be issued shortly containing all of the results of the investigations involving simultaneously transient temperature and load.

Quirk, John and Harman, C.G., Properties of a Tin Oxide-Base Ceramic Body. (Journal of the American Ceramic Society, 37, p. 24, 1954). 413

Abstract

Some thermal and mechanical properties were measured for tin oxide-matrix compacts which nominally were composed of 99% by weight tin oxide (SnO_2) and 1% zinc oxide (ZnO). The sintered compacts were similar in strength to high-fire mullite procelains, had superior resistance to thermal shock, and had high thermal conductivity. The tin oxide body might be expected to give good service under conditions of severe thermal shock and in an oxidizing atmosphere at temperatures up to 1500° F.

Scheetz, Howard, An Investigation of the Theoretical and Practical Aspects of the Thermal Expansion of Ceramic Materials. (Quarterly Progress Report No. P1-1273-M-11, Cornell Aeronautical Laboratory, Inc., November 30, 1961). 414

Abstract

The thermal expansion of composite materials (including multiple-phase ceramics) can be predicted from the thermoelastic properties of the individual phases providing the resulting body is microscopically continuous and none of the phases enter into a solid solution with any other phase. The degree of validity of the theory is dependent only upon the completeness with which the internal stresses which arise from thermoelastic dissimilarities are described once the appropriate thermoelastic properties are correctly defined and measured. The case in which the composite body is macroscopically isotropic is of immediate interest and will be treated exclusively in the following discussions.

In previous reports, several simplifying assumptions have been used to permit computation of the thermal expansion of two phase ceramic bodies from existing data. These assumptions will be reconsidered and a more complete theory for multiple-phase ceramic bodies will be presented in this report. It will be shown that the most important factor toward improved correlation between thermal expansion theory and experiment which has been obtained is the determination of the intrinsic elastic properties of each ceramic phase. This conclusion led to the adoption of ultrasonic techniques for the measurement of the elastic moduli of ceramic bars. The ultrasonic apparatus was arranged to permit measurements on bars having the same geometry as normally used in the quartz dilatometer. Thus, the elastic moduli could be measured for the series of specimens previously prepared for dilatometer measurements.

Gross reduction in the elastic moduli due to finite porosity resulted in attempts to produce high-density ceramic bodies without sintering-agent additions. Efforts were initially directed toward producing high-density $MgAl_2O_4$ spinel. Experimental work was done utilizing apparatus for induction-heated hot-pressing to obtain high-density spinel and mixtures of Pyrex glass with spinel. The Pyrex-Spinel system has been analyzed in detail to define the theoretical thermoelastic properties.

Preliminary studies of intrinsic stress wave losses in polycrystalline ceramics were begun to determine the feasibility of detecting the onset of thermally induced microcracks. It was found that the scattering of stress waves by pores exceeded all other losses in the ceramics tested, again necessitating high-density bodies. A brief review of ultrasonic pulse techniques, stress wave velocity relations, and loss mechanisms in polycrystalline bodies are included in this report.

Schwartz, Bernard, Thermal Stress Failure of Pure Refractory Oxides. (Journal of The American Ceramic Society, 35, 12, pp. 325-333, December, 1952). 115

Abstract

An investigation was carried out to study the thermal stress failure of three pure, dense refractory oxides, namely alumina, stabilized zirconia, and magnesia. Thermal stress resistances were determined by means of a direct test and by calculation from the physical properties of the material. The properties measured included strength, elasticity, and thermal expansion. All the tests were conducted within the temperature range 25° to 1500° C. For hollow cylindrical specimens, heated uniformly from the inner surface, resistance to fracture was expressed quantitatively by the heat flow at steady state required to cause fracture. This resistance was found to be a function of (1) the physical properties of the material, (2) the temperature range of testing, and (3) the temperature distribution within the specimen.

Smoke, E.J., Development of Refractory Ceramics That Can Be Processed at Temperatures Considerably Lower Than Their Maximum Use Temperature. (Quarterly Progress Report No. 5, Contract No. NOw 61-0211-c, School of Ceramics, Rutgers, The State University, December 1, 1961 - March 1, 1962). 416

Abstract

A study was initiated on the densification mechanism of high alumina bodies that utilized the presintering process in their fabrication. Evidence is presented that the initial or presintering fire promotes the formation of phases that act as potent fluxes for the alumina in the final fire. A program is set up to determine the nature of the phases formed in the initial firing.

An initial attempt to utilize the devitrification mechanisms for producing a high quality refractory composition is reported. A 92% alumina composition was flame sprayed resulting in a glass that contains some alumina crystals. Differential thermal analysis and X-ray analysis indicated that a devitrifiable glass was produced.

High alumina bodies in the Al_2O_3-MgO system will be investigated in order to determine and control the densification of alumina. Experimental work will be carried out in a high temperature resistance furnace capable of reaching temperatures in excess of 2000° C. in an extremely short time interval. Firings will be carried out in atmospheres of vacuum, dry hydrogen, and helium.

Sokolowski, Marek, Thermal Stresses in a Spherical and Cylindrical Shell in the Case of Material Properties Depending on the Temperature. (Rozprawy Inzynierski CLXIX, 8, 4, pp. 641-667, 1960). 417

Abstract

This work deals with determined problems of thermal elasticity with reference to stresses which occur in the walls of a pipe (cylindrical shell) or hollow sphere (spherical shell) in the case when their internal and external surfaces are heated to different temperatures.

Stavrolakis, J.A., and Norton, F.H., Measurement of the Torsion Properties of Alumina and Zirconia at Elevated Temperatures. (Journal of the American Ceramic Society, 33, 9, September 1, 1950). 418

Abstract

A precise instrument for measuring the torsion properties of refractories up to temperatures of 1500°C. is described. The twist is measured by sapphire mirrors mounted on the specimen itself. The mechanical properties of dense alumina and dense stabilized zirconia were measured at various temperatures. Higher ultimate strengths were reached than those reported for other bodies.

Sutherland, R. D., Manville, S. M., Schneider, K. J., Shook, R. G., and White Jr., F. M., Thermal Stresses in Perforated Plates and Bodies of Revolution. (General Dynamics Corporation, AFOSR - 1050, TM-349-35, June, 1961). 119

Abstract

Methods are derived for the determination of thermal stress in perforated plates and bodies of revolution. The perforated plate problem, being two-dimensional, is found to be amenable to the complex analysis of Muskhelishvili. The problem of thermal stresses in bodies of revolution is solved in an exact manner by restricting the problem to the aft end of the ogive-shaped body considered.

To obtain solutions to the two-dimensional problems of thermal stresses in perforated plates, the complex analysis of Muskhelishvili is employed with the additional use of conformal mapping. The conformal mapping makes necessary the use of special techniques in order to apply the boundary conditions. Two different examples are presented: 1) thermal stresses in a square plate containing a central circular perforation, and 2) thermal stresses in a circular plate containing a central star-shaped perforation.

The problem of thermal stresses in ogival bodies of revolution, being a three-dimensional problem, must be approached in a different manner. To begin with, a coordinate system is developed based on the classic ogive shape which can approximate a variety of low aerodynamic drag shapes. Thermoelastic and thermoplastic equations are then developed in this coordinate system. The thermoelastic problem is then solved in this coordinate system by a combination of stress functions and a numerical technique. Closed form solutions are obtained by considering only the aft end of the ogive.

Swanson, C. G., Van Der Maas, C. J., and Huang, P. C., Allowable Stresses for Elevated Temperature Structures. (Technical Report No. ASD-TR-61-8, April, 1962, Flight Dynamics Laboratory, Aeronautical Systems Division, Air Force Systems Command 120

Wright-Patterson Air Force Base, Ohio, Project No. 1367, Task No. 14002, under Contract No. AF 33(616)-6904 by Martin Marietta Corporation, Baltimore Division, Baltimore, Maryland).

Abstract

Time-dependent methods of analysis for columns, stiffened and unstiffened plates, and torsional members have been developed and programmed for the IBM-709 digital computer. The important material behaviors, i.e., soaking at temperatures, elastic and plastic strain, creep and residual stress and strain under varying temperature and load inputs, can be accounted for in the digital solutions.

Two illustrative examples for obtaining allowable stresses are shown: the first for a stable structure in combined tensile and bending and the second for a column subjected to time-dependent displacements due to creep. These two examples are sufficiently typical to demonstrate the applicability of the procedures developed in this report or other procedures which give the stress-strain-deflection time history of a structure.

Taylor, R.E., and Nakata, M.M., Study of Thermal Properties of Refractories. (First Quarterly Progress Report on Contract No. AF 33(657)-7136, ARPA Order No. 24-61, Project No. 002, Contractor's Report No. AI-6829, October, 1961, Atomics International, A Division of North American Aviation, Inc., Canoga Park, California). 421

Abstract

A status report is presented on the development of the transient thermal property apparatus described in Parts I and II of WADD-TR-60-581. Modifications and improvements of the apparatus are described, and results of measurements of the thermal diffusivity of tantalum at 1400° and 1500° C. are given. The status of thermal property measurements by existing techniques is also included.

Thielke, Norman R., (The Pennsylvania State University), Refractory Materials for Use in High Temperature Areas of Aircraft. (Materials Laboratory Contract No. AF 33(616)-139, Project No. 7350, WADC Technical Report 54-467, July, 1955. Wright Air Development Center, Air Research and Development Command, United States Air Force, Wright-Patterson Air Force Base, Ohio.) 422

Abstract

The fracture patterns of TiC-Cermet stator blades which had been exposed to a simulated service test and the microstructures of these materials were investigated. An attempt to correlate fracture patterns and microstructures was unsuccessful.

The oxidation behavior of cermets was studied theoretically and experimentally. Theoretically, the tendency to oxidize was derived from an oxidation free energy plot for the reactions representing the complete oxidation of Ti-, Nb-, Ta-, Si-, Fe-, Co-, Ni-, and Cr-carbides. Experimentally, the oxidation behavior of carbide and metal powders was investigated using the differential thermal analysis technique. The oxidation resistance of carbide powders increased approximately in the following order: VC, TiC, NbC, B_4C, WC, ZrC, TaC, Cr_xC_y, SiC. A similar classification has been found for metal powders with Cr and Si ranking best.

The ternary system TiC-TaC-NbC has been investigated, using sintering temperatures up to 2530° C. The reactions were almost complete, indicating a complete solid solution throughout the system. Of all the sintered compositions in this system, TiC exhibited the greatest oxidation resistance.

The sintering and shrinking behavior of oxide mixtures simulating the oxides which are being formed during the oxidation of carbide Cermets, has been studied in search for compositions which form a dense and adherent oxide film.

Aluminum titanate bodies with additions of alumina, manganese carbonate and cosium Pyrex glass showed a modest increase in strength which was offset by an increase in thermal expansion.

An analysis of the applicability of thermal shock tests has been made. It follows that such tests are indispensable for the empirical determination of the maximum stresses as well as for a check on the theory of thermal shock. However, they are not suited as material tests.

A static method to measure the two thermal stress resistance factors R and R' is described and measurements on porous and dense titania, steatite, cordierite, and β-spodumene bodies are presented.

Ungar, Edward W., Applications of Materials to Solid-Rocket Nozzles. (Astronautics, p. 24, April, 1961). 423

Abstract

The ever-increasing performance of propellants, headed for combustion temperature of 8300°F. in the next decade, stimulates the drive for better nozzle materials, better known and more cleverly applied.

Vanderbeck, R. W., Wilde, H. D., Lindsay, R. W., and Daniel, C., Statistical Analysis of Behavior in the Transition Temperature Zone. (Welding Research Supplement of Welding Journal, 18, pp. 325s-332s, 1953). 424

Abstract

Numerous keyhole Charpy impact tests were conducted in the ductility transition temperature range of several steels. In all these tests, the familiar pattern of behavior was evident, in which either high energy values (portraying tough behavior) or low energy values (portraying brittle behavior) were usually obtained, with few intermediate values. It was found that the relationship representing the percentage of brittle breaks at each temperature coincided, within the limits of error, with a cumulative frequency distribution curve, such as shown in Fig. 6. This curve becomes a straight line when plotted on probability paper (Fig. 8). Behavior in the transition zone is then represented by two parameters of this line: (1) the temperature at which 50% of the specimens behave in a brittle manner, called the median transition temperature, and (2) the slope of the line, which may be expressed in terms of the width of the transition range between the 10 and 90% (or any other) brittle-expectancy points.

The best straight line (the least-squares regression line) through the points representing percent brittle behavior at each temperature is obtained by a statistical method called probit analysis, which is described. Use of this method also permits calculation of confidence limits within which the true median transition temperature and the true width of the transition range will lie 95% of the time.

Methods are then described for comparing and for judging differences between two or more regression lines.

Finally, examples are given which indicate how precise, as judged by confidence limits, the estimates of transition temperature and of range may be when different numbers of tests are performed and when they are distributed in different patterns.

Wachtman, Jr., J.B., and Lam, Jr., D.G., Young's Modulus of Various Refractory Materials as a Function of Temperature. (Journal of the American Ceramic Society, 42, 5, pp. 254-260, 1959). 425

Abstract

Young'a modulus as a function of temperature was determined by a dynamic method for single-crystal sapphire and ruby and for polycrystalline aluminum oxide, magnesium oxide, thorium oxide, mullite, spinel, stabilized zirconium oxide, silicon carbide, and nickel-bonded titanium carbide. For the single crystals, Young's modulus was found to decrease

linearly with increasing temperature from 100°C. to the highest temperature of measurement. For all the polycrystalline materials, except silicon carbide, stabilized zirconium oxide, and spinel, Young's modulus was found to decrease approximately linearly with increasing temperature until some temperature range characteristic of the material was reached in which Young's modulus decreased very rapidly and in a nonlinear manner with increasing temperature. This rapid decrease at high temperature is attributed to grain-boundary slip. Stabilized zirconium oxide and spinel were found to have the same rapid decrease in Young's modulus at high temperature, but they also had a decidedly nonlinear temperature dependence at low temperature.

Warren, D.S., Castle, R.A., and Gloria, R.C., An Evaluation of the State-of-the-Art of Thermo-Mechanical Analysis of Structures. (Technical Report No. WADD TR 61-152, prepared under Contract No. AF 33(616)-6880 by Douglas Aircraft Company, Inc., Santa Monica, California. Flight Dynamics Laboratory, Aeronautical Systems Division, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, January, 1962). 426

Abstract

The state-of-the-art of thermo-mechanical analysis of flight structures is evaluated on the basis of reliability. The Matrix Force Method, the Matrix Displacement Method, and the Direct Analog Method are considered to be representative of the principal structural theories. The various schemes for discrete idealization of flight structures are treated separately. The discussion of reliability is referenced primarily by an extensive series of analyses cases. Comparisons with experimental data and exact solutions are shown for several structures. Consideration is given to the dual objectives of structural analysis, i.e., both stresses and flexibility; flexibility predictions are considered as basic data for both aeroelastic and vibration analyses. It is concluded that the fallibility of the analyst is the major negative factor in the reliability of the state-of-the-art. Recommendations are given for improvement.

NOTCH SENSITIVITY
AND
STRESS CONCENTRATION

ARMOUR RESEARCH FOUNDATION OF ILLINOIS INSTITUTE OF TECHNOLOGY

Ault, R. T., and Spretnak, J. W., Initial Yielding and Fracture in Notched Sheet Molybdenum. (Technical Documentary Report No. ASD-TDR-62-223, Project No. 7351, Task No. 735106, April, 1962, Directorate of Materials and Processes, Aeronautical Systems Division, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio). 427

Abstract

Initial yielding and fracture initiation behavior of wrought stress-relieved and recrystallized molybdenum was investigated at room temperature. The effect of notch severity and grain size on the nature of plastic flow in notched sheet tensile specimens was investigated by means of photoelastic coatings. The nature of fracture initiation in notched sheet tensile specimens was studied through the use of pre-polished and etched tandem notched specimens.

Analyses of the unnotched tensile properties for the recrystallized material, according to the Griffith-Orowan theory for crack propagation and the Cottrell criterion for crack initiation, show that the effective surface energies for crack propagation and crack initiation are the same order of magnitude, which is 10^3 ergs/cm^2. This finding is supported by the experimental observation that no microcracks were found.

Plastic flow regions determined experimentally from the photoelastic coating studies were shown to be in good agreement, both qualitatively and quantitatively, with theoretical results predicted by elastic-plastic stress analyses.

Initial yielding at the notch root was found to occur at the same nominal stress level for a given material condition, independent of the magnitude of the stress concentration factor. This nominal stress in the notched section was nearly equal to the smooth tensile yield stress.

Limited dislocation density measurements, determined by etch pit techniques, revealed that a quantitative measurement of strain at the root of a sharp notch in recrystallized molybdenum is difficult to obtain by such a technique.

Feldman, Myra S., Stress-Corrosion Cracking of Stainless Steel. (E.I. duPont de Nemours & Company, Explosives Department-Atomic Energy Division, Technical Division, Savannah River Laboratory, printed for the United States Atomic Energy Commission, Contract AT(07-2)-1, DP-683, Metals, Ceramics, and Materials, (TID-4500, 17th Edition)). 428

Abstract

References on the stress-corrosion cracking of stainless steel have been abstracted from the open literature through September, 1961.

Galin, L.A., Contact Problems in the Theory of Elasticity. 429
(Translated from the Russian by Mrs. H. Moss. Department of Mathematics, School of Physical Sciences and Applied Mathematics, North Carolina State College, October, 1961).

Hollomon, J.H., The Notched-Bar Impact Test. (Transactions 430
AIME, 158, pp. 298-327, 1944).

Abstract

The interpretation of notched-bar impact results has been a matter of controversy since the introduction of more or less standard tests by Fremont, Charpy, and others at the turn of the century. Many investigators have contributed to the understanding of the significance of such tests. Several symposiums have been held with the express purpose of discussing the significance and interpretation of the impact tests. It is not the purpose of this paper to review all these contributions to the development of the knowledge on this subject, but rather to present an interpretation of notched-bar impact tests that appears to be in agreement with the available published data.

Fundamentally, the interpretation discussed in this paper of the brittle failure of some steels in notched-bar impact test is similar to the qualitative analysis presented by Ludwik in the 1920's.

The present paper concerns itself primarily with the behavior of notched impact specimens. The effects of strain rate, temperature, and stress distribution, which are discussed with reference to the impact specimen, apply just as well to the behavior of metal at the bases of notches in any engineering structure. All that is necessary is to determine the stress distribution in the structure at the base of the notches.

Hoyt, S.L., Notched Bar Testing. (Metals and Alloys, Vol. 7, 431
January, continued in February and April, and concluded in May, 1936.)

Abstract

The present title for the type of testing under consideration here was selected because it seems worth while to show that the Charpy and Izod tests are not tests which primarily bring out the ability of a metal to resist

shocks or impacts but, rather, that they are tests which show how the metal responds to the stress system produced by a notch. I don't mean to imply that metals always show the same behavior in static and impact loading - frequently they don't - but rather that the effect of impact belongs in a separate category. I hope that this position will not be construed as being arbitrarily taken, for it seems to me to be dictated by the behavior of metals in static and dynamic loading, on the one hand, and in the plain and notched conditions, on the other. I shall try to make this clear as the impact effect and the notch effect are being discussed.

Imgram, A.G., Gilbert, A., Marschall, C.W., Bartlett, E.S., Hahn, G.T., Holden, F.C., and Ogden, H.R., Second Quarterly Progress Report on Further Investigation of Notch Sensitivity of Refractory Metals. (Contract No. AF 33(616)-7604, Task No. 73521, Aeronautical Systems Division, Battelle Memorial Institute, March 31, 1962). 432

Abstract

This is the Second Quarterly Progress Report on the research program "Further Investigation of Notch Sensitivity of Refractory Metals." The program is intended to:

(1) Provide a better understanding of the influence of fabrication and heat-treatment variables on notch sensitivity,

(2) study fracture toughness, and

(3) investigate mechanisms of notch embrittlement.

Imgram, A.G., Gilbert, A., Marschall, C.W., Bartlett, E.S., Hahn, G.T., Holden, F.C., and Ogden, H.R., Further Investigation of Notch Sensitivity of Refractory Metals. (Contract No. AF 33(616)-7604, Task No. 73521, Aeronautical Systems Division, Battelle Memorial Institute, Columbus, Ohio, June 30, 1962). 433

Abstract

This is the Third Quarterly Progress Report on the research program "Further Investigation of Notch Sensitivity of Refractory Metals." The program is intended to:

(1) Provide a better understanding of the influence metallurgical variables on notch sensitivity,

(2) study fracture toughness, and

(3) investigate mechanisms of notch embrittlement.

Imgram, A.G., Holden, F.C., Ogden, H.R., and Jaffee, R.I., Notch Sensitivity of Refractory Metals. (Transactions of Metallurgical Society of AIME, 221, p. 517, June, 1961). 434

Abstract

The tensile and notch tensile properties of four refractory metals (molybdenum, tungsten, niobium (columbium), and tantalum) and one alloy (Mo-0.5Ti) were investigated. All the materials were evaluated in bar from, and the molybdenum and Mo-0.5Ti also were studied in sheet form. The notch sensitivity of each material was evaluated on the basis of several criteria, including the notch-unnotch strength ratio, the ductility transition, and the fracture transitions.

Imgram, A.G., Mallett, Manley W., Koehl, Billy G., Bartlett, Edwin S., and Ogden, Horace R., Notch Sensitivity of Refractory Metals. (Technical Report No. ASD-TR-61-474, Project Nos. 7351 and 7381, Task Nos. 73521 and 73812, Directorate of Materials and Processes, Aeronautical Systems Division, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, prepared under Contract No. AF 33(616)-7604, by Battelle Memorial Institute, Columbus, Ohio, January, 1962). 435

Abstract

The effects of interstitial oxygen and hydrogen on the tensile and notch tensile properties of tantalum and columbium were investigated. The tensile and notch tensile properties of Ta-10W and F-48 columbium alloy were determined also. Oxygen and hydrogen additions resulted in notch-sensitive behavior at higher temperatures than for pure Ta and Cb, and, similarly, transition temperatures are increased by the interstitial additions. The F-48 alloy also shows notch-sensitive behavior at higher temperatures and has a higher transition temperature than columbium. The Ta-10W alloy was not notch sensitive, and retained excellent ductility at -420 F.

In addition, reaction kinetics in the tantalum-hydrogen system were studied.

Inglis, C.E., Stresses in a Plate Due to the Presence of Cracks and Sharp Corners. (Transactions Institute of Naval Architects, 55, p. 219, 1913). 436

Abstract

The methods of investigation employed for this problem are mathematical rather than experimental, and this mathematical treatment is given in some detail in Part II of this paper. Part I is a summary of the more important results and conclusions, and in this part mathematics are kept as far as possible in the background.

The main work of the paper lies in the determination of the stresses around a hole in a plate, the hole being elliptic in form. The results are exact, and are consequently applicable to the extreme limits of form which an ellipse can assume.

Kuhn, Paul, and Figge, I.E., Unified Notch-Strength Analysis for Wrought Aluminum Alloys. (Technical Note D-1259, National Aeronautics and Space Administration, May, 1962). 437

Abstract

A simple engineering method is presented for predicting the strength of notched parts made from wrought aluminum alloys under static loading or under repeated loading near the fatigue limit. Assumed to be known are tensile strength, elongation, and modulus of elasticity; in certain cases, the stress-strain curve must be known; also needed are "Neuber constants," which are given in the report. Notch configurations ranging from mild notches to cracks are considered. A large number of comparisons between experimental and predicted results are presented.

Lea, Professor F.C., The Strength of Materials as Affected by Discontinuities and Surface Conditions. (Journal of the Society of Glass Technology, 16, p. 182, 1932). 438

Abstract

The paper describes experiments to determine the effect of discontinuities and surface conditions of metals on the behavior of the materials when subjected to cycles of repeated stress.

When test specimens are prepared from metals by turning and finishing the surface in the lathe or grinding machine, the safe range of stress that can be indefinitely applied to the metal at a specified mean stress can generally be expressed as a fraction of the ultimate tensile stress. This safe range, for a mild steel, at zero mean stress is about equal to the

tensile strength of the material. If, however, during the test the surface is subjected to corrosive conditions (for example, it may be kept wetted by distilled water or by an acid or salt solution), the safe range of stress for say 10 million repetitions may be lowered to much less than one-half of the breaking strength and the tests described show that the fatigue range may become very small. In other words, under such conditions, failure in time will occur at very small stress ranges. Photomicrographs are given showing interpenetration of corrosion lines into specimens that had not broken after more than 100 million repetitions of stress.

Cooled and flat plate springs are heated during manufacture and are finally heat-treated and left in the black condition. The paper describes experiments which show that the safe range of repetition stress for such springs may be less than 30 percent of the safe range of the same material when the surface layers have been removed by machining and grinding. It is also shown that cold-drawn wires, although apparently quite smooth and exhibiting no surface discontinuities, have a fatigue range of from 16 to 60 percent of that which might be expected from a machined specimen of the same composition and same tensile stress. It is suggested, and evidence given, that the decarbonized surface is not sufficient to account for the difference.

The effects of scratches, screw threads, grooves, keyways, drilled holes, and other discontinuities in considerably reducing the safe fatigue range, both under cycles of stress and blows, are discussed and illustrated. Reference is made to experiments on specimens subjected to stress cycles as cathodes, nascent hydrogen being liberated at their surfaces and penetrating the metal, and it is shown that discontinuity produced by this gas does not lower the fatigue range, but it changes the character of the fracture.

The effect of nickel deposits on the surfaces of metals subjected to repeated stresses is discussed. It is suggested that the phenomena are explained by assuming stress concentrations at discontinuities and that in the case of heat-treated and cold-drawn materials imperceptible discontinuities at grain boundaries lead to the failure at low ranges of stress.

Lubahn, J.D., On the Applicability of Notch Tensile Test Data to Strength Criteria in Engineering Design. (Transactions ASME, 79, p. 111, 1957). 439

Abstract

This paper gives a brief review of the information which currently can be obtained from notched tensile tests, followed by a discussion of the fact that the applicability of this information to manufacturing problems is so limited as to be almost useless for many engineering purposes. Finally, there is a consideration of what kind of information is necessary for rational design, and how such information might be obtained.

ARMOUR RESEARCH FOUNDATION OF ILLINOIS INSTITUTE OF TECHNOLOGY

Ludley, J.H., and Drucker, D.C., A Reversed-Bend Test to Study Ductile to Brittle Transition. (Welding Journal Research Supplement, December, 1960). 440

Abstract

The use of a sharply bent beam as a test specimen to explore the influence of material and environment on the borderline between ductile and brittle behavior of structural steels is proposed by the authors.

The proposal is made to use very sharply bent beams as test specimens to explore the influence of material and environment on the borderline between ductile and brittle behavior of structural steels. Although far removed from the homogeneous cylindrical test specimens reported on previously, the reversed-bend test offers real hope of becoming a simple shop- and field-inspection test of direct and understandable physical meaning. At the least, it provides a reproducible laboratory test for the preliminary study of such factors as the amount of precompression, aging, temperature of testing, machined vs. as-rolled surface, etc. Some results are given for project **E**-steel, A-7, and T-1. All show brittle behavior in tension following large precompression and all are adversely affected by aging.

Ludley, J.H., and Drucker, D.C., Size Effect in Brittle Fracture of Notched Steel Plates in Tension. (Serial No. SSC-135, First Progress Report of Project SR-158, to the Ship Structure Committee, Brown University, Providence, Rhode Island, under Department of the Navy, Bureau of Ships Contract NObs-78440, BuShips Index No. S-R 0090301, transmitted through Committee on Ship Structural Design, Division of Engineering and Industrial Research, National Academy of Sciences-National Research Council, under Department of the Navy, Bureau of Ships Contract No. NObs-72046, BuShips Index No. NS-731-036, Washington, D.C., November 24, 1961). 441

Abstract

Direct experimental evidence is presented here to support the hypothesis that a Griffith-type theory is not the critical condition for the initiation of brittle fracture in steel plates. The data indicate almost complete size independence for notched, compressively prestrained, Project **E** steel specimens of 6 2/3 inch, 1,0 inch, and 20 inch widths, which had geometrically similar dimensions in the plane of the plate but were of the same thickness.

Manjoine, M.J., Size Effect on Notched Rupture Time. (ASME Publication, Paper No. 61-WA-280, 1961). 442

Abstract

A size effect can be demonstrated for elevated-temperature notched rupture strength. As the size is increased, the rupture strength approaches that of the unnotched bar. For a material which is notch strengthened, the rupture time of a notched bar is primarily that of the initiation time which decreases as the size is increased, since the stress gradient and strengthening effect at the base of the notch is decreased. For a material which is notch sensitive or weakened, the initiation time and propagation time both increase with specimen size, therefore, the rupture time increases with size. The fracture propagation is higher in the peripheral direction of the notch because of the higher rupture damage accumulation in this higher stressed region.

Neuber, Heinz, Exact Elastic Solutions Concerning the Notch Effect of Plates and Bodies of Rotational Symmetry. (Transactions of the Principal Conference in Wurzberg, Journal of Applied Mathematics, 13, 6, p. 439, December, 1933). 443

Orner, G.M., and Hartbower, C.E., Notch Sensitivity in High Strength Sheet Materials. (Report of Progress No. 13, Metals Joining Branch, Watertown Arsenal Laboratory, Massachusetts, September 30, 1960). 444

Abstract

In the previous progress report a precracking technique for sheet Charpy specimens was described and data presented to show the validity of results so obtained. It was demonstrated that by precracking not only was the energy to initiate cracking eliminated, but that the major loss in fracturing brittle materials, i.e., the excess elastic energy loss, was also eliminated. This technique has proved to be highly successful for precracking sheet Charpy specimens in most steel and titanium sheet materials. Later work, however, in aluminum and certain very tough stainless steels, (not severely embrittled by cooling to -196° C) showed that cracks could not be formed in these materials by reverse bending without severely deforming the specimens. Furthermore, in extremely brittle materials, particularly in the welded condition, complete fracture of the specimens sometimes occurred during the precracking operation. For these reasons fatigue was investigated as an alternative method of precracking.

Petch, N.J., The Transition Temperature in Notched Specimens. 445
(A conference on Brittleness in Metals, held at R. and D. Branch Culcheth Laboratories, November, 1, 1957, UKAEA Industrial Group Report 145-RD/C, H. M. Stationery Office, Paper No. 2, pp. 18-20.)

Abstract

Equations (2) and (3) represent the criterion for brittle fracture fairly well. The important factors that can be varied are grain size, the strength of the dislocation locking, and the friction on a free dislocation.

$$\beta T_c = \ln B - \ln(16q\gamma' - 4\sqrt{18\gamma}) - \ln\left[\frac{\mu}{3\pi(1-\nu)\gamma}\right]^{1/2} - \ln l^{-1/2} \quad \ldots (2)$$

$$\varepsilon T_c = \sigma_o^* + c - (16q\gamma' - 4\sqrt{18\gamma})\left[\frac{\mu}{3\pi(1-\nu)\gamma}\right]^{1/2} l^{-1/2} \quad \ldots (3)$$

Peterson, R.E., An Investigation of Stress Concentration by Means of Plaster-of-Paris Specimens. (Mechanical Engineering, 48, p. 1449, 1926). 446

In this paper the author shows that the determination of stress-concentration factors by means of plaster-of-paris specimens is a simple means of obtaining results which are close to or on the safe side of fatigue results. Mathematical stress-concentration factors based on the theory of elasticity, as well as photoelastic factors, differ considerably from fatigue results for small holes and small fillets.

Tests to determine stress concentration in loaded members due to holes, fillets, grooves, and threads are described.

Three-dimensional problems in stress distribution, which cannot be solved photoelastically, may be investigated by tests of plaster-of-paris specimens, which are not difficult to make and may be machined very nicely.

Pospisil, Joseph Lee, Stress Concentration in a Notched Specimen of Brittle Material, Subjected to Tri-Axial Loading. 447
(ASTIA - AD-153 744, Div. 25/6, 1957).

Abstract

An investigation was made on notched specimens of brittle material (1) to determine the stress concentration under conditions of triaxial loading (tension and flexure), and (2) to determine whether or not the stress

concentration factor was dependent on load ratios as well as specimen dimensions. Specimen dimensions were held constant throughout this study. The material used for specimens was No. 1 molding plaster, and tests were performed which indicated that it displayed the characteristics of an ideally brittle material. A slight variation of stress concentration with load ratio was apparent under triaxial loading conditions.

Sachs, G., and Lubahn, J., Effects of Notching on Strained Metals. (The Iron Age, 150, 15, p. 31; 150, 16, p. 49, 1942). 448

Abstract

The first part of this abstract was concerned primarily with correlating existing experimental data, with particular attention to the work of Kuntze. Some variations in properties at high and low temperatures were reviewed, along with several paragraphs on the effects of additional bending.

The second and concluding part correlates the experimental evidence relating to notch effects in tensile specimens. Herein the authors discuss stress distribution and some conceptions of cohesive strength.

Strauss, E.L., Effects of Stress Concentrations on Laminate Strength. (Plastic Technology, August, 1959). 449

Abstract

Results of a comprehensive study on glass fiber-reinforced polyester laminates are given. A study of failures in glass fabric-reinforced plastic laminates containing stress concentrations was conducted by Martin with specific attention to single holes, multiple holes, cutouts, notches, and fillets.

Voorhees, H.R., Freeman, J.W., and Herzog, A.J., Trends and Implications of Data on Notched-Bar Creep Rupture. (ASTM Paper No. 61-WA-232, 1961). 450

Abstract

Extended research on creep rupture of notched specimens, conducted at the University of Michigan under Air Force sponsorship, is analyzed along with recent publications of others. The combined results suggest that notch strengthening is general for all alloys studied under some test conditions and is not specific to individual materials or to a given

ductility level. Quantitative explanation of notch-rupture behavior in terms of unnotched-specimen properties is handicapped by present uncertainties in the basic factors controlling creep-rupture life under variable multiaxial stress.

Wells, A.A., The Mechanics of Notch Brittle Fracture. (Welding Research, 7, pp. 34N-56N, April, 1953). 451

Abstract

Notch brittle fracture at temperatures just below the transition temperature, in material showing usual ductility in the tensile test, with statically applied external loads, is shown to occur when these external loads are sufficient to satisfy two separate conditions of initiation and propagation.

In structures possessing no residual systems either of plastic strain or high elastic stress, the initiation loading condition is shown to be that of general yield, where a plastic zone entirely crosses the body, and embraces the root of a notch. Loads sufficient to cause this are generally higher than those met in service. When residual stress systems either of plastic strain or high elastic stress are present due to the local heating and cooling from fusion welding, brittle fractures may be started from notches or hot cracks in commercial mild steel, below the transition temperature, with small external loads or even none at all.

A method is described which makes it possible to measure the energy absorbed in plastic flow along the surfaces of a propagating brittle fracture, by means of the temperature wave created. A notch brittle material has been shown experimentally to possess, at a given temperature, a minimum surface energy of crack propagation, as first suggested by Irwin. Thus, if a fracture is initiated in a structure, but the rate of release of stored elastic energy with increase of length of the crack is insufficient to provide the minimum surface energy of the material, then the crack will not propagate. On the other hand, the surface energy of the material can have values above the minimum, so that the type of brittle breaking strength formula based on surface energy, and first proposed by Griffith, cannot be used indiscriminately. In general, it appears that the brittle breaking loads of large specimens are determined by the initiation process, where the influence of stresses other than those due to external loads is excluded, while the breaking loads of small specimens are controlled by minimum surface energy.

These results have been applied to explain certain notch brittle fractures which have recently occurred in large welded structures. In some cases these fractures were initiated in butt welds, and propagated transversely in the material on either side. At the present time this type forms a fair proportion of the total number of fractures recorded. The initiation of the fracture has been shown to occur because of the coincidence of an initial crack and plastic stretching, in the direction of a weld, of the adjacent material due to local heating and cooling; the first stages of crack

propagation rely on a residual stress field of yield point magnitude which is the end result of this stretching. The later stages of catastrophic propagation then depend on the lower service stress in the whole structure. Although residual stress relief, or the removal of macroscopic weld cracks, would seem to be adequate to prevent this form of failure under the limited conditions discussed above, where the structure is statically loaded, it is obvious that other metallurgical and practical factors must be considered before any positive recommendations can be made to cover all cases.

Wundt, B.M., A Unified Interpretation of Room-Temperature Strength of Notched Specimens as Influenced by Their Size. (ASME Publication No. 59-Met-9, Presented April 29 to May 3, 1959). 452

Abstract

This paper proposes a generalized concept of material behavior in the presence of sharp notches or cracks, which embraces the notch-strengthening of small bars and the notch-weakening of large bars. Quantitative explanation of notch-strengthening of small bars follows from the experimental work of G. Sachs and others, and the interpretation of notch-weakening of large bars, the geometric size effect, is obtainable with the help of Griffith-Irwin approach using the strain-energy-release concept. Experimental notch strength versus size curves for notch-tension and notch-bending tests are plotted in an especially useful log-log co-ordinate system. An analytical expression was derived to approximate the foregoing experimentally observed, continuous variation of notch strength. A relationship was derived between the notch strength and relative notch depth for cylindrical tension bars with different outside diameters. The plots indicate a continuity of notch-strength behavior with varying size and varying notch depth.

CREEP

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Alesch, C.W., Klein, B., and Robe, W., Prediction of Creep Effects in Aircraft Structures. (Technical Report WADD-TR-60-411, Part 2, Flight Dynamics Laboratory, Aeronautical Systems Division, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, February, 1962). 453

Abstract

The method presented in WADD TR 60-411 Part I for predicting deformations in aircraft structures undergoing creep is reviewed. Modifications and simplifications of this method are considered and a simplified version of the original method is presented. Box beam tests were used to investigate the simplified method. The outcome of these tests indicated the accuracy of the method in predicting deformations in aircraft structures undergoing creep was in the same order of accuracy as that usually experienced in redundant analysis procedures.

The power law for expressing creep relations is found redundant in solution. Its usefulness appears chiefly in the display of creep test data. Current creep prediction methods, such as the Larson-Miller and Manson Haferd methods, appear as linearizing approximations for creep-relations with the result that inaccuracies in predicting very long and very short creep life restrict their usefulness. An approach to creep prediction based on creep-rupture history for establishment of creep laws is proposed. Relationships between tension - and creep - test data are examined experimentally with respect to single and repetitive load applications. General relationships are examined with the outcome that a general approach to creep prediction in all metallic materials appears improbable.

Beauchamp, E.K., Baker, G.S., and Gibbs, P., Impurity Dependence of Creep Aluminum Oxide. (Technical Documentary Report No. ASD TR 61-481, April, 1962, Directorate of Materials and Processes, Aeronautical Systems Division, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio). 454

Abstract

Polycrystalline sintered compacts of doped Gulton Alucer MC alumina have been deformed in three point beam loading in the temperature range 1000° to 1350° C. Creep consisted of a transient deformation (ϵ_{tr}) superposed on a steady state deformation ($\epsilon_{s.s} = C_1 \cdot t$). The steady state creep rate of specimens doped with MgO or $MnCO_3$ from 50 to 5000 ppm by weight were fit to the expression A exp(-E/kT). The activation energy E was found to be 130 Kcal/Mole independent of added impurity. The constant A was independent of $MnCO_3$. A decrease in A by a factor

of 3-5 in samples doped with MgO may have been due to presence of some large grains. It is suggested that steady state creep of fine grained polycrystalline alumina is controlled by diffusion of vacancies.

Transient creep (ϵ_{tr}) occurring on application of stress approximated the relation

$$\epsilon_{tr} = C_2 \left[1 - \exp(-t/\tau_1)\right] + C_3 \left[1 - \exp(-t/\tau_2)\right]$$

On removal of the load, recovery was observed which followed the relation

$$\epsilon_{rec.} = C_2 \left[\exp(-t/\tau_1)\right] + C_3 \left[\exp(-t/\tau_2)\right]$$

where, as indicated, the amplitude and functional dependence was about the same as for the transient creep. One of the relaxation times was observed to fit the expression $\tau_o \exp(-E_1/kT)$ where E_1 was about 30-40 Kcal/Mole. It is suggested that this is related to relaxation of stress by grain boundary sliding.

Berkovits, Avraham, Determination of the Creep Deflection and Lifetime of Aluminum-Alloy Multiweb Box Beams Subjected to Varied Loads at Constant Temperature. (Technical Note D-1265, National Aeronautics and Space Administration, June, 1962). 455

Abstract

A method was developed for computing the deflection and lifetime of multiweb box beams subjected to creep under varied loads at constant temperatures. The method of analysis is based on the life-fraction rule and materials creep data obtained from constant-load and constant-temperature tensile creep tests. Calculated deflection and lifetime results are compared with corresponding test data from multiweb box beams fabricated from 2024-T3 aluminum-alloy sheet and tested at 400° F. under cyclic creep loads. An equivalent-stress concept is utilized in a portion of this study to reduce the varied-load creep problem to creep under constant stress.

Cass, T.R., and Achter, M.R., Oxide Bonding and the Creep-Rupture Strength of Nickel. (N.R.L. Report 5803, High Temperature Alloys Branch, Metallurgy Division, U.S. Naval Research Laboratory, Washington, D.C., June 22, 1962). 456

Abstract

A technique for measuring the creep and rupture strength of nickel specimens bonded by sintered oxide layers has been developed. This

technique is used in the investigation of the role of grain-boundary oxide in the oxidation strengthening of nickel during creep at 817° C. From the inverse dependence of the rate of bonding on the thickness of the starting oxide, it is suggested that the rate of diffusion of Ni^{++} through NiO is the controlling process at the start of sintering. Comparisons of the creep and rupture strength and of the microstructure of sintered couples with conventional creep specimens suggest that rupture in nickel is prevented by load-bearing, intergranular layers of oxide.

Chang, Roger, High Temperature Creep and Anelastic Phenomena in Polycrystalline Refractory Oxides. (Journal of Nuclear Mathematics, 2, p. 174, 1959). 457

Abstract

High temperature creep and anelastic phenomena in polycrystalline Al_2O_3 and BeO were studied. The activation energies for both "steady-state" creep and grain boundary relaxation are approximately 2.0×10^5 calories per mole for Al_2O_3 and 1.2×10^5 calories per mole for BeO. Addition of small amounts of Cr_2O_3 or La_2O_3 to Al_2O_3 and of MgO to BeO introduces additional grain boundary relaxation peaks at lower temperatures and reduces grain boundary viscosity. The beneficial effects of these additives in improving the high temperature ductility of refractory oxides are briefly discussed.

A correlation between the experimentally observed "steady-state" creep rates and those calculated according to the Nabarro-Herring mechanism from self-diffusion data for BeO suggests that the Nabarro-Herring mechanism may predominate in the creep of polycrystalline BeO and possibly other oxides at high temperatures and low stresses. Further verification of the observation is needed.

Chipman, R. D., Stress-Strain-Temperature-Time Relationships for Refractory Materials. (NAA-SR-3205, Contract: AT(11-1)-Gen-8, Issued: December 1, 1958, Atomics International, A Division of North American Aviation, Inc.) 458

Abstract

Creep tests are proposed to determine the temperature and time dependence of gross mechanical behavior of refractories. Different types of tests are discussed briefly with respect to the economics of obtaining large quantities of creep data for engineering design use. To illustrate proposed methods isothermal bending tests were conducted on some BeO and SiC bodies over a range of temperature from room to 2730°F. Testing time varied from a fraction of a minute to 24 hours. In the bending

apparatus SiC heating elements are used, two-point specimen loading is imposed at a constant rate and deflection is recorded continuously. Testing procedures and their influence on data are described. Modulus of rupture and relatively short time creep data are presented, and stress-strain-temperature-time relationships represented by such data are discussed. Limitations on the interpretation and use of these data are discussed, and the suggestion is made that bending creep data be applied only to bending studies. Parameters are derived which relate bending loading intensity to strain condition, temperature, and time. Future work is outlined.

Coleman, Bernard, D., Time Dependence of Mechanical Breakdown Phenomena. (Journal of Applied Physics, 27, 8, pp. 862-866, August, 1954). 459

Abstract

A phenomenological theory of the time dependence of mechanical breakdown phenomena is presented which is applicable to creep failure of oriented polymeric filaments under tensile stresses. In using the theory, one makes assumptions about the distribution of breaking times in ensembles of filaments which are bearing constant loads and then proceeds to calculate the distribution of lifetimes under other stress histories, e.g., loads increasing linearly with time and sinusoidal loads. The a priori assumptions used here permit a calculation of the dependence of observed tensile strengths on both the sample size and the rate of loading. Experiments involving drawn 66 nylon monofilament yarn are cited to illustrate how the parameters which describe the average lifetime under dead load behavior of a yarn may be used to calculate its tensile strength distribution when measured with a constant rate of loading apparatus.

Crussard, C., and Friedel, J., Theory of Accelerated Creep and Rupture. (Proceedings of a Symposium held at the National Physical Laboratory, May 31st - June 2nd, 1954, p. 243, H.M. Stationery Office). 460

Abstract

Creep and Fracture of Metals at High Temperatures.

Dewhirst, D.L., and Sidebottom, O.M., Inelastic Design of Load Carrying Members, Part V. Theoretical and Experimental Creep Analyses of Beam-Columns. (WADD Technical Report 60-580, January, 1962). 461

Abstract

A theory is presented for constructing load-creep deflection curves for beam-columns at any specified time. The stress-strain-time relation for the material is assumed to be represented by an isochronous stress-strain diagram approximated by an arc hyperbolic sine curve (see Equation 16). A program has been written for the IBM 650 digital computer to calculate points on moment-curvature curves for a general I-section. The theory uses these curves and the successive approximations procedure by Newmark.

The experimental part of the investigation included tests of rectangular- and T-section beam-columns made of 17-7Ph stainless steel and tested at 972° F. Several slenderness ratios were considered. The beam-columns were subjected to a constant axial load located either at the centroid of the section or at an eccentricity of 15 percent of its depth and to a constant transverse load at midspan of sufficient magnitude to produce a linear elastic bending stress when acting alone of $0.50\sigma_o$.

Dorn, John E., Some Fundamental Experiments on High Temperature Creep. (Proceedings of a Symposium on Creep and Fracture of Metals at High Temperatures, held at the National Physical Laboratory, 31st of May to 2nd of June, 1954, p. 89, H.M. Stationery Office). 462

Abstract

At high temperatures, the creep strain, ε, appears to be a function of a temperature (T) compensated time (t), namely $te^{-\Delta H/RT}$, and the stress. X-ray analyses and plastic properties reveal that the same structures are developed at the same values of $te^{-\Delta H/RT}$ following creep at the same stress. Thus,

$$\varepsilon = f(te^{-\Delta H/RT})$$

for the same stress. When the creep rate, $\dot{\varepsilon}$, is evaluated as a function of stress, σ, for the same structure

$$\dot{\varepsilon} = Se^{-\Delta H/RT}\phi(\sigma)$$

where S depends on the structure and

$$S\phi(\sigma)\begin{cases} S'e^{B\sigma} & B\sigma > \sim 1.4 \\ S''\sigma^n & B\sigma < \sim 1.4 \end{cases}$$

Although B and n appear to be insensitive to structural changes attending creep of annealed alloys, they decrease with increasing solute additions and cold working. Transients attending loading and unloading and the coincidence of the activation energy for creep, ΔH, with that for self-diffusion suggest that high temperature creep might be ascribed to a dislocation climb process.

ARMOUR RESEARCH FOUNDATION OF ILLINOIS INSTITUTE OF TECHNOLOGY

Gerard, George, and Papirno, Ralph, Investigation of Creep Buckling of Columns and Plates, Part IV. Column Creep Buckling Theory and Correlation with Experiments. (WADC Technical Report 59-416, July, 1961). 463

Abstract

A creep buckling theory is developed based upon fundamental concepts of a mechanical equation of state to represent the time dependent behavior at instability of columns and also a time dependent formulation of the governing differential equation and stability criterion. The predictions of this theory as well as those of other classical stability hypotheses are then correlated with recent experimental data of creep buckling of 2024-0 aluminum alloy columns. A simplified approach for prediction of creep buckling is also presented and this is correlated with test data on columns of various aluminum alloys, titanium alloys, and 17-7PH stainless steel. Conclusions are drawn as to the predictive value of classical stability approaches and to certain important difficulties in correlating the data which are related to the short time failure behavior of columns at elevated temperatures and which seem to have been overlooked in the past.

Manson, S. S., and Mendelson, A., Optimization of Parametric Constants for Creep-Rupture Data by Means of Least Squares. (Memorandum 3-10-59E, National Aeronautics and Space Administration, March, 1959). 464

Abstract

An objective method utilizing least squares is presented for the determination of the optimum parametric constants for stress-rupture data. The method is applied to both isostress and isothermal data for the parameters proposed by Larson and Miller, Manson and Haferd, and by Dorn. Several examples are treated in detail, and it was found that the method gives good results. It is shown that the values of the constants for the parameter proposed by Manson and Haferd are not critical as long as T_a and log t_a appear in the proper combination. In addition to optimization, the chief utility of the method lies in the fact that it gives the same results for a given set of data no matter who makes the analysis, which is not the case for the graphical methods presently employed.

Moon, Donald P., and Simmons, Ward F., Methods for Conducting Short-Time Tensile, Creep, and Creep-Rupture Tests under Conditions of Rapid Heating. (OTS PB 151078, DMIC Report 121, December 28, 1959, Office of the Director of Defense, 465

Research and Engineering, Defense Metals Information Center, Battelle Memorial Institute, Columbus, Ohio).

Abstract

The need for very short-time high-temperature tensile and creep data for the design of supersonic aircraft and missiles has led to the development of a group of rapid-heating tests. These tests are of relatively brief duration, often only 1 or 2 seconds. They require special equipment and techniques for the rapid heating of test specimens and for the accurate measurement and control of temperature, stress, and strain during test.

In addition to very short-time constant-temperature tensile and creep tests after rapid heating, this group of tests includes those in which pre-loaded specimens are heated rapidly until rupture or are heated to a test temperature for the determination of time for a given deformation or for rupture.

The equipment and test methods used by 15 different organizations in conducting tests involving rapid-heating methods are reviewed in this report. A wide variety of testing methods are being used by these organizations because of the equipment available for the testing and the type of data desired. The more important variations in equipment and technique are described in detail. The main advantages and disadvantages of the various techniques are discussed, and applicable requirements of ASTM-recommended practices are cited.

The methods used for the rapid heating of test specimens include resistance, induction, radiant, and hot-fluid heating. These are described in detail, along with methods for controlling specimen temperature. The role of specimen design is discussed, and several specimen contours are illustrated. The spot welding of thermocouples, the calibration of radiation pyrometers, and the merits of various types of load cells, strain extensometers, and recorders are also covered in this report.

Although no formal conclusions are presented in the report, the wide variety of test practices in use for conducting rapid-heating tests suggests the need for standardization of procedures. Only if this is done can the data from various laboratories be used interchangeably.

Mordfin, Leonard, Halsey, Nixon, and Greene, Gary E., Investigations of Creep Behavior of Structural Joints under Cyclic Loads and Temperatures. (Technical Note D-181, National Aeronautics and Space Administration, October, 1959). 466

Abstract

Eighty-two structural joint specimens were tested to evaluate the effects of cyclic loads and cyclic temperatures on creep and rupture. The specimens included riveted joints of 2024-T3 clad aluminum alloy, and

riveted and spot-welded joints of 17-7 PH (TH 1050) stainless steel. The results of these tests show a wide variance but indicate certain trends which permit the estimation of the cyclic creep behavior of joints.

An analysis of the effects of stress concentration on the tensile rupture strength of riveted joints is presented in appendix A. This, together with data from several other laboratories, shows that the effects are small for joints fabricated from notch ductile materials and conventional rivets.

Odqvist, F.K.G. (Sweden), On Theories of Creep Rupture. 467
(Contribution to IUTAM Symposium on Second Order Effects in Elasticity, Plasticity, and Fluid Dynamics, Haifa, April, 1962).

Abstract

Creep rupture is the more or less brittle fracture that occurs if a test piece, e.g., of a structural steel, is subjected to a constant tensile load at elevated temperature, say, above 400° C. Recent progress in metal physics has taught us that this phenomenon is very complex indeed. It occurs in most crystalline solids and depends upon the pile-up and coalescence of dislocations and the formation of voids in or between the grains of the crystal structure. These phenomena, however, show individual characteristics, inherent to each material and there does seem to exist a series of mechanisms involved. Nevertheless, if for a creep rupture test, initial stress σ'_{t0} is plotted against life time t^{x} on a log/log basis, curves of very much the same type will be obtained for a number of structural materials. Most of these curves show two distinct straight parts, the one corresponding to longer life time definitely steeper than the one corresponding to shorter life time. Usually longer life time means more brittle fracture than shorter life time, where fracture is more ductile.

Rabotnov, Y.N., The Effect of Changing Loads During Creep. 468
(Proceedings of a Symposium on Creep and Fracture of Metals at High Temperatures, held at the National Physical Laboratory, May 31st to June 2nd, 1954, H.M. Stationery Office, p. 221).

Servi, Italo S., and Grant, Nicholas J., Creep and Stress Rupture Behavior of Aluminum As a Function of Purity. (Transactions AIME, Journal of Metals, 3, p. 909, 1951). 469

Abstract

Extensive data of minimum creep rates and rupture times for high purity and commercial aluminum confirm the existence of a transition range from the low temperature-type to the high temperature-type behavior. The data are analyzed in line with the suggested theories of deformation of metals.

Stowell, E. Z., and Wah, Thein, (Southwest Research Institute), A Unified Theory for Creep Buckling under Normal Loads. (Journal of the Aerospace Sciences, 29, 6, pp. 658-661, June, 1962). 470

Abstract

A general theory of creep buckling, with the initial imperfection as a parameter, is developed for the case of normal loading. A hyperbolic-sine law is used to describe the process of creep. The theory is believed to be applicable to, among other structures, columns, tubes, and possibly conical shells. The wall of the structure is idealized as a sandwich in order to simplify the integration of the equations.

Experimental data on columns and tubes, from two different sources, are compared with the predictions of the theory.

Wachtman, Jr., J.B., and Maxwell, L.H., Plastic Deformation of Ceramic-Oxide Single Crystals. (Journal of the American Ceramic Society, 37, 7, p. 291, 1954). 471

Abstract

It was found that plastic deformation takes place in periclase above 1100° C., in rutile above 600° C., and in sapphire above 900°C. The mechanism is slip; in saphire (0001) is the slip plane and (1120) is the slip direction. All creep curves for sapphire in tension show the same qualitative features. Each consists of three stages: a stage of increasing creep rate (sometimes called an incubation period), a stage of large but decreasing creep rate (sometimes called first-stage creep), and a stage of small and nearly constant creep rate (sometimes called second-stage creep). The so-called third-stage creep, characteristic of metal behavior, has not been noted. Plastic deformation increases the electrical resistivity of sapphire at constant temperature.

Wah, Thein, and Gregory, R. K., Studies in the Creep Buckling of Circular Cylinders and Conical Shells. (Southwest Research Institute, Project No. 7063, Task No. 70524, Under Contract No. 33(616)-6914, ARL 184, Aeronautical Research Laboratory, Office of Aerospace Research, United States Air Force, Wright-Patterson Air Force Base, Ohio, December, 1961). 472

Abstract

This report presents theoretical and experimental work on the creep collapse of aluminum circular cylinders of various lengths and end conditions and of aluminum circular truncated cones of various geometries. These shells were subjected to a uniform external pressure and elevated temperature (300-500° F.).

The results of tests to determine the creep properties of the aluminum alloy 6061-T6 are also presented.

Agreement between theoretical predictions of collapse time and test results varied from fair to good. Generally, the results for the cylinders showed much better agreement than those for the cones.

CRACK PROPAGATION

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Baker, B.R., Dynamic Stresses Created by a Moving Crack. 473
(ASME, Paper No. 61-APMW-28, 1961).

Abstract

A solution is obtained for the case in which a semi-infinite crack suddenly appears and grows at constant velocity in a stretched elastic body. The problem, one of mixed boundary values on a half plane, is solved by transform methods including the Weiner-Hopf and Cagniard techniques. Among the graphical results presented is the time variation of the transverse stress at a fixed point on the line of fracture as the tip of the crack approaches. Asymptotic forms for the stresses near the crack tip are also obtained and are compared with results of other studies in crack propagation.

Carlsson, Janne, Experimental Studies of Brittle Fracture Propagation. (Transactions of the Royal Institute of Technology, Stockholm, Sweden, Mechanical Engineering 6, No. 189, 1962). 474

Abstract

The velocity of crack propagation in plates of mild steel is studied. In this connection two different methods for the measurement of the velocity have been used.

The first is based upon measurement of the high frequency impedance across the crack. This impedance varies linearly with the crack-length. For the second one makes use of capacitive crack detectors, cemented to the surface in the form of thin foils.

An attempt is made to explain the forking of the cracks observed in some cases and the observed variation of the propagation velocity.

Cheverton, K.E., Crack Propagation - An Engineer's Approach. 475
(Engineering Materials and Design, February, 1962).

Abstract

The mechanism of crack propagation is of paramount importance to engineering designers, and a great deal of work has been done on this problem. The author reviews the principal features of these studies.

Craggs, J.W., On the Propagation of a Crack in an Elastic-Brittle Material. (Journal Mech. Phys. Solids, Vol. 8, pp. 66-75, 1960, Pergamon Press Ltd., London). 476

Abstract

The Griffith theory of brittle cracking is extended to a dynamic problem, in which a semi-infinite crack in an infinite medium is extended by finite forces. The conclusion is drawn that the force required to maintain a steady rate of extension of the crack decreases as the rate increases. It is also observed that various criteria which may be assumed for crack division lead to limiting velocities of propagation of a single crack.

Frenkel, Y.I., Theory of Reversible and Nonreversible Cracks in Solids. (Technical Memorandum 1387, National Advisory Committee for Aeronautics, 1952). 477

Abstract

The Griffith crack theory is reviewed and certain shortcomings of this theory are discussed. A new description for the shape of a crack is given which takes into account the atomic structure of material. Through consideration of the total energy of the system and the shape of the crack, expressions for crack behavior are derived which are considered to remedy the defects of the Griffith theory.

Gerberich, William, Stress Distribution about a Growing Crack Determined by the Photoelastic Coating Method. (Technical Report No. 32-208, Contract No. NAS 7-100, National Aeronautics and Space Administration, April 4, 1962). 478

Abstract

An experimental stress analysis technique using a birefringent coating is reported for determining the stress distribution about a slowly growing crack. The maximum error of the test method for a large strain gradient is found to be less than 10 percent. For a plate with an internal crack, the experimentally determined stress distribution compares favorably with two numerical solutions. Comparison of stresses about an internal or double-edge crack to those about a single-edge crack indicates that the isochromatics bend over to about 45 deg with the plane of the crack in the former and are inclined at about 60 deg in the latter. Also, the stresses for a single-crack tip vary as the inverse square root of the radius, while the stresses for a double-crack tip follow an $r^{-1/4}$ law more closely.

Gilman, John J., Propagation of Cleavage Cracks in Crystals. 479
(Journal of Applied Physics, 27, p. 1262, 1956).

Abstract

The role of crack propagation velocity in the cleavage of crystals and aggregates is emphasized in this paper. The available data on crack propagation in elastic media are summarized, showing that this phenomenon is adequately understood at present. For inelastic media, it is postulated that in addition to the Griffith Criterion two critical velocity conditions must be satisfied or crack propagation cannot occur. One critical velocity pertains to propagation through a crystal, and the other to propagation through an aggregate. The first critical velocity depends on the rate at which plastic glide can absorb energy at a crack tip and the number and size of cleavage steps that a crack front contains. These quantities are estimated. The second critical velocity accounts for the dependence of fracture stress on grain size in aggregates and interprets other experimental behaviors of aggregates which contradict previous interpretations.

Irwin, G. R., Analysis of Stresses and Strains near the End of 430
a Crack Traversing a Plate. (Journal of Applied Mechanics,
24, pp. 361-364, 1957).

Abstract

A substantial fraction of the mysteries associated with crack extension might be eliminated if the description of fracture experiments could include some reasonable estimate of the stress conditions near the leading edge of a crack particularly at points of onset of rapid fracture and at points of fracture arrest. It is pointed out that for somewhat brittle tensile fractures in situations such that a generalized plane-stress or a plane-strain analysis is appropriate, the influence of the test configuration, loads, and crack length upon the stresses near an end of the crack may be expressed in terms of two parameters. One of these is an adjustable uniform stress parallel to the direction of a crack extension. It is shown that the other parameter, called the stress-intensity factor, is proportional to the square root of the force tending to cause crack extension. Both factors have a clear interpretation and field of usefulness in investigations of brittle-fracture mechanics.

Irwin, G. R., Relation of Crack-Toughness Measurements to 481
Practical Applications. (Paper No. 62-MET-15, Mechanics
Division, U. S. Naval Research Laboratory, Washington, D. C.,
1962).

Abstract

Crack-toughness measurement techniques which provide a critical value of the stress intensity K for crack propagation have been discussed in a number of previous publications. This paper discusses the meaning and applicability of K_c and K_{Ic} measurements in various practical applications. It is pointed out these measurements permit estimates of: (a) conditions for fracture mode transition, (b) toughness standards consistent with anticipated fracture-failure mechanisms, and (c) a relation between crack size and tensile stress for crack propagation. During the past five years developments of knowledge in the field of fracture mechanics have tended to enhance the importance of applications (a) and (b). On the other hand variable amounts of slow incremental crack extension have been noted due to fatigue, stress corrosion, and other causes which reduce the accuracy of estimates pertaining to application (c). Studies of slow crack-growth mechanics of various kinds are needed to give more specific meaning to estimates of critical conditions for crack propagation.

Jenkins, P. C., and Morrison, J. D., An Investigation of the Crack-Propagation Resistance of High-Strength Alloys and Heat-Resistant Alloys. (Southern Research Institute, Birmingham, Alabama, 5024-1256-III, June 27, 1961, prepared under Bureau of Naval Weapons, Contract NOw 61-0392-d, Bimonthly Progress Report No. 3, April 24, 1961 through June 23, 1961). 452

Abstract

An evaluation of the crack-propagation properties of molybdenum sheet materials was made in the temperature range from about 50° F. to 1500°F. Emphasis was placed on locating the brittle-ductile transition temperature of each material and on detecting any elevated-temperature sensitivities possibly due to strain aging.

The "base-line" data obtained from these commercially available materials will be compared with data taken from experimental materials to be evaluated later in the program.

Matthews, C.O., Jacobson, M.I., Jahsman, W.E., and Ward, W.V., Beryllium Crack Propagation and Effects of Surface Condition. (WADD Technical Report 60-116, Lockheed Aircraft Corporation, Missiles and Space Division, July, 1960). 453

The mechanical properties of beryllium sheet with various surface finishes were investigated. The best properties were obtained on sheet which had been etched to remove surface defects caused by machining.

Ductility was low in all cases, being limited by the presence of notches and by preferred orientation in the sheet. Ductility was increased by heating to 400° to 600° F.

The fatigue endurance limit was as high as the static tensile strength, and was improved by etching. Impact tests were found to be most suitable for distinguishing between various surfaces.

Theoretical analyses were made of the effect of including residual stress in the Griffith crack theory, and of the dynamic stress at the leading edge of a crack in a uniaxially stressed plate.

Mote, Jr., C.D., and Frisch, J., Crack Propagation in Aluminum-Foil Laminates. (Transactions of the ASME, Journal of Basic Engineering, Paper No. 61-WA-131, Nov.-Dec. 1961). 4.4

Abstract

Crack propagation in 4 x 10 inch laminated specimens of 1100 H-19 aluminum foil under uniaxial tensile loads perpendicular to the crack direction has been investigated. While the crack behavior is similar to that found in monolithic sheets, the laminates exhibit a brief arresting of crack growth before onset of sudden fracture. It was further established that the Griffith-Irwin energy-dissipation rate is a constant for any particular laminate configuration.

Saibel, Edward, The Speed of Propagation of Fracture Cracks. (Fracturing of Metals, ASM, p. 275, 1948). 4.5

Abstract

The phenomenon of the so-called "brittle fracture" of metals, in particular, steel, has been the subject of much attention in recent years principally because of its connection with the catastrophic failure of ship plate, one of the characteristics of this brittle rupture being the extreme speed with which the crack is propagated along the plate. Experimental studies of the speed of propagation of the fracture crack have been carried out by Hudson and Greenfield, and by Davis, Troxell, Parker, and O'Brien.

It is the object of this paper to derive a theoretical expression for the speed of propagation of a brittle crack in a metal and to show in a general way its dependence on both the hydrostatic component of the stress system and the temperature. The results will be compared with what experimental evidence is available.

Schilhansl, Max J. (Brown University), Rapid Propagation of a Crack in a Brittle Material. (Department of the Navy, Bureau of Ships NObs-65917, BuShips Project No. NS-731-034, for Ship Structure Committee, March, 1955). 486

Abstract

The mechanics of the continuum is applied to the problem of the propagation of a crack in a plate that is in a 1-dimensional state of stress induced by static external loads. The crack is assumed to have reached the point where the rapid increase of the velocity of propagation begins. The initial crack is assumed to be at the center of the plate and to consist of a slit perpendicular to the direction of the external load p; the length of the crack is 2L(t) at time t. In the analysis, the actual plate is replaced by a model consisting of 2 beams connected by strings perpendicular to the axes of the beams from $x = \pm L$ to the ends of the plate. The analysis shows that the velocity of propagation of the crack is given by

$$\sqrt{c_0 + c_1 \frac{1}{L^2} + \frac{2}{3} qL}.$$

If the velocity V_{xo} and acceleration $\left(\frac{dv_x}{dt}\right)_o$ are known at a time t when the crack has length L_o, the constants of integration are given by

$$c_1 = -L_o^3 \left[\frac{1}{2}\left(\frac{dv_x}{dt}\right)_o - \frac{1}{3} q\right], \text{ and}$$

$$c_0 = V_{x_o}^2 + \frac{L_o}{2}\left(\frac{dv_x}{dt}\right)_o - qL_o.$$

Srawley, J.E., The Slow Growth and Rapid Propagation of Cracks. (Physical Metallurgy Branch, Metallurgy Division, U.S. Naval Research Laboratory, Washington, D.C., NRL Report No. 5617, May 17, 1961). 487

Abstract

The application of fracture mechanics to crack-propagation testing and fracture of high-strength, thin-section materials has been examined in relation to the development of a fracture failure from a small, semi-elliptical, surface crack origin. In the absence of environmental influences, slow crack growth will be appreciable only if the ratio of the fracture toughness for the thickness under consideration, K_c, to the so-called "plane strain" fracture toughness, K_{Ic}, exceeds a certain value.

An expression for this lower-bound value has been developed. If the ratio does not exceed the lower bound, direct calculations of fracture stress from the initial crack dimensions and the K_{Ic} value can be made. Otherwise, the Irwin criterion that the critical crack length must exceed twice the section thickness applies. Environmental effects are important but are normally a factor only in material selection and not in fracture mechanics calculations. The effects of repeated loading are being investigated at a number of centers, and some preliminary conclusions have been reached. Further research regarding both of these effects is needed.

Stroh, A.N., A Simple Model of a Propagating Crack. (Journal Mech. Phys. Solids, Vol. 8, pp. 119-122, 1960. Pergamon Press, Ltd., London). 488

Abstract

A model of a crack is developed in which the surface energy in the Griffith treatment is taken to depend on the temperature and strain rate. It is shown that such a crack shows a transition from brittle to ductile behavior as the temperature is raised.

Tetelman, A.S., and Robertson, W.D., Direct Observation and Analysis of Crack Propagation in Iron - 3% Silicon Single Crystals. (Technical Report No. 5 to the Office of Naval Research, Contract NONR 609(28), Hammond Metallurgical Laboratory, Yale University, New Haven, Connecticut, February, 1962). 489

Abstract

Microcracks, 10^{-2}cm long on $\{100\}$ planes, are produced by precipitation of hydrogen in iron-3% silicon single crystals when hydrogen is introduced either by cathodic charging, or by quenching from a hydrogen atmosphere at a high temperature. Plastic deformation produced during growth of cracks can be observed as arrays of decorated dislocations in the volume of the crystals. The slip planes involved in plastic deformation around the tip of a crack have been identified and they are in accord with those predicted from theoretical considerations. Because of the discontinuous nature of the process of crack growth under internal pressure, it is possible to obtain values for the energy expended in plastic deformation, γ_p, as a function of crack length. For cracks about 10^{-2}cm long, γ_p is of the order of the intrinsic surface energy of the crystal, γ_s. Values for the distance to which plastic deformation extends from the tip of a stationary crack were measured and they compare favorably with values predicted from theoretical considerations.

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Westergaard, H.M., Stresses at a Crack, Size of the Crack, and the Bending of Reinforced Concrete. (Journal of the American Concrete Institute, November-December, 1933). 490

Abstract

A study of the individual crack leads to a revision of the conventional picture of the stresses in a reinforced concrete beam. At a crack the compressive strains in the direction of the beam are not proportional to the distance from a neutral axis. The revised picture suggests the relative advantage of the smaller sizes of reinforcing bars.

Williams, D., Crack Propagation Properties of Thin Sheet - Some Recent Results and Their Impact on Design. (U.D.C. No. 539.219.2 : 620.191.33 : 669.715-415, C.P. No. 564). 491

Abstract

The concept of scale-effect introduced in Ref. 5 to account for dissimilar critical crack lengths in similar flat sheets is placed in better perspective by relating it to Griffith's well-known work on crack propagation. The results of recent experiments are quoted that confirm the reliability of the approach via scale effect and also confirm the semi-empirical formula for relating critical stresses in flat sheets to those in corresponding cylinders.

Winne, D.H., and Wundt, B.M., Application of the Griffith-Irwin Theory of Crack Propagation to the Bursting Behavior of Disks, including Analytical and Experimental Studies. (ASME Publication No. 57-A-249, presented December, 1957). 492

Abstract

This paper presents the results of bursting tests of large, bored, and effectively notched disks removed from long rotor forgings. Most of the tests were conducted at room temperature. For the particular disk geometry employed, the net average tangential stress at bursting speed was as low as 25,000 psi for brittle behaving materials and as high as 77,000 psi for materials approaching ductile behavior. These correspond to 26 percent and 92 percent of yield strength, respectively. The Griffith-Irwin theory of crack propagation is adapted to the calculation of G_c, fracture toughness, from notched-disk bursting-test results. It is shown that G_c from disk tests agrees with G_c obtained from slow notched-bend tests; and therefore appears to be a property of material, largely independent of specimen size.

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The actual magnitude of G_c permits the classification of forgings by the degree of their susceptibility to brittle fracture in the presence of discontinuities. G_c and the ratio K_{ys} of room temperature bursting strength to yield strength are found to correlate well with the material Charpy V-notch fracture appearance transition temperature. As the latter is reduced, G_c and K_{ys} are increased.

Yoffe, Elizabeth H., The Moving Griffith Crack. (Philosophical Magazine, 42, pp. 739-750, July, 1951). 493

Abstract

The stress field is calculated about a straight crack moving through an elastic medium. The stresses depend on the velocity and reduce to Inglis' solution when the velocity is zero. The results may be applied to the spicular fracture of glass.

MATERIALS ENVIRONMENT

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Central Research Laboratory, Crucible Steel Company of America, Research on Workable Refractory Alloys of Tungsten, Tantalum, Molybdenum, and Columbium. (WADD Technical Report 61-134, May, 1961, Aeronautical Systems Division). 494

Abstract

This project was undertaken to determine the potential of the tungsten- and tantalum-rich alloys of the W-Ta-Mo-Cb system for high-strength structural applications at temperatures above 2500° F. Twenty specific compositions, including binary, ternary, and quaternary alloys were investigated.

Several homogeneous and contamination-free ingots of each alloy were melted by use of a specially designed consumable-electrode vacuum-arc melting unit. Special techniques were developed for the impact extrusion of these alloys, and all alloys were successfully extruded at temperatures from 2500° to 4000° F.

Creep and tension tests were conducted on the as-extruded samples at 3000° F. in vacuum. The high-temperature strength of the tungsten-rich alloys was increased considerably by the addition of columbium, and the high-temperature strength of the tantalum-rich alloys was appreciably increased by additions of molybdenum and tungsten.

One alloy (88.6W - 5.7 Mo - 5.7 Cb) had a tensile strength of 62,000 psi at 3000° F.; several other alloys had tensile strengths in excess of 50,000 psi. These strengths were attained by a combination of solid-solution strengthening and strain hardening.

On the basis of results of this investigation, the tungsten- and tantalum-rich alloys of the W-Ta-Mo-Cb system offer excellent promise as wrought materials for structural applications at very high temperatures.

Dunn, E. J., Survey and Future Trends of Graphite Technology. (Project 7381, Task 73812, ASD TR 61-353, Contract AF 33 (616) 6288, February, 1962). 495

Abstract

Graphite technology has advanced in the last three years to the point where it is now broadly known that graphites are a family of materials whose properties can be varied widely and controllably by adjusting its degree of anistropy. For example: pyrolytic graphite can be made one of the best heat insulators in one direction and a heat conductor at least as good as copper in the plane normal to this direction. Obviously, it is planar in nature, and most properties in these directions are strongly interrelated.

Since a degree of at least local plasticity can often be designed into a graphite for some specific applications, less deviation from conventional design approaches is required in contrast to most brittle materials.

There is a general need for closer coordination and collaboration between the decision-making designer and the materials engineer. This need becomes even more evident from studies of the newer or horizon materials. In graphites this need is particularly important since their physical properties can be varied rather widely and a change made in one property is often adverse to some other property. With such interrelation it is mandatory that the material be designed for the specific application; it is precisely here that the close-working relation between the materials man and the designer is required. The design problems are generally solved through trial and error processes since intelligent measurements with which to specify design requirements are often lacking. Material property adjustments must be made as dictated by experimental results before success can be attained where the ultimate in properties is required. This complexity precludes the treatment of graphite as a stocked item to be used indiscriminately.

New processes and a group of coordinated nondestructive tests have made and will continue to make further improvement in graphite reliability. The problem of coating graphite to prevent oxidation is now fairly well understood by some, and is on its way to solution by materials people in general.

Future trends in graphite development include the following: (1) Fabrication of ZT recrystallized or hot-worked type graphites (National Carbon Patent Grade) based on knowledge of starting materials, control of anisotropy, and consideration of specific or likely design requirements. (2) Development of graphites incorporating cloth, fibers, and felts for lighter and higher strength-to-weight ratios. (3) Production of advanced shapes in pyrolytic graphite. (4) Production of thicker sections of free-standing pyrolytic graphite. (5) Development of metallo pyrolytic graphites as possible replacements for the conventional pyrolytic graphite. (6) Improvement of dependability of graphites.

Gatzek, Leo E., and Peck, James L.H., Trends and Future Developments in Aerospace Materials. (Report No. TDR-930 (2411) TN-1, Aerospace Corporation, El Segundo, California, Contract No. AF 04(647)-930, prepared for Deputy Commander Aerospace Systems, Air Force Systems Command, United States Air Force, Inglewood, California, December 15, 1961). 196

Abstract

This report embodies a survey of the current state of the materials art and certain developmental trends indicated for the period to 1970.

Stresses and skin temperatures of manned vehicles can be expected to increase as vehicle operations evolve kinetically from Mercury orbital missions through Dyna Soar boost-glide re-entry and eventual lunar re-entry. Many desirable and promising materials for load-bearing and nonstructural use under the natural and induced environments of aerospace operations simply cannot be produced yet in the desired quantities or shapes. Because of a lack of oxidation-resistant alloys and suitable coatings for the refractory metals, their use has been restricted to nonstructural applications. The availability of structural-grade uniform alloy sheet is still not optimum for molybdenum and columbium alloys. Tungsten and tantalum alloy sheet of usable sizes is not generally available. The behavior of these and other refractory metals under conditions of stress, temperature, and oxidizing atmosphere is not too well understood and requires considerable study. Graphite is not currently available in the necessary sizes or uniformity for immediate application as a structural material; the need is shown for refractory carbide development.

A general evaluation of promising new materials includes superalloys such as Nicrotung, Rene' 41, Udimet 700, and Inco 717C. Projected improvements for refractory metals are examined, together with brief discussions of composites, plastics, foams, metal fabrics, filament-wound structures, and the use of metals as fuels. Coatings, elastomers, and adhesives are discussed. Attention is also directed toward the cryogenic behavior of both metals and nonmetals.

Grinthal, R. D., New High Temperature Intermetallic Materials. 497
(American Electro Metal Division, Firth Sterling, Inc. WADC Technical Report 53-190, Part 5, ASTIA Document No. AD110684, Aeronautical Research Laboratory, Contract No. AF 33(616)-3198, Project 7350, Task 70634, Wright Air Development Center, Air Research and Development Command, United States Air Force, Wright-Patterson Air Force Base, Ohio).

Abstract

Six ternary systems were investigated.

Copper, when added to molybdenum disilicide, does not remain as such in equilibrium, but forms a copper silicide. No beneficial effects on any physical properties due to copper addition were noted. Oxidation resistance of $MoSi_2$ is seriously impaired by even small copper additions.

The chromium corner of the chromium-molybdenum-silicon system contains materials of moderate strength, good stress-to-rupture properties, and excellent resistance to oxidation at elevated temperatures. The silicon corner contains materials of poor strength and excellent oxidation resistance. The molybdenum corner contains materials of good strength and poor oxidation resistance. All these materials exhibited brittle behavior under impact loading.

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All compositions investigated in the titanium-molybdenum-silicon system had the common characteristics of moderate strength, good oxidation resistance, fairly high electrical resistivity and poor resistance to impact loading.

Several compositions in the chromium-titanium-silicon system have been identified by chemical and X-ray diffraction analysis. This system, which contains many intermetallic compounds, has demonstrated that the possibility of binding a hard material in a metal matrix under equilibrium conditions is rather remote.

The investigation of the system titanium-aluminum-nickel centers on the triangle formed at the center of the system by NiAl, NiTi, and TiAl. Phases present in this area are complex and difficult to identify with certainty. Some physical data is given, but the investigation of this system is not yet completed.

It has been found that the intermetallic compound Cr_2Ti can exist at equilibrium with free copper present. Copper additions to Cr_2Ti seem to improve some properties somewhat, but they have an extremely deleterious effect on resistance to oxidation at elevated temperatures.

Gross, Oliver, A Linear Program of Prager's Notes on Linear Programming and Extensions - Part 60. (Memorandum RM-2993-PR, The Rand Corporation, April, 1962). 493

Abstract

For the problem of minimizing the integral $\int_0^1 f(x)dx$ subject to the constraints

$$-f(x) \leq xg(y) \leq f(x) \qquad \text{if } 0 \leq x \leq y \leq 1,$$

$$-f(x) \leq xg(y) - x + y \leq f(x) \qquad \text{if } 0 \leq y \leq x \leq 1,$$

the author exhibits solutions and proves both that they satisfy the constraints and that they have the extremizing property.

The problem, proposed by W. Prager, arose in an elastico-plastic, structural-design context.

Klopp, W.D., Summary of the Fifth Meeting of the Refractory Composites Working Group. (Office of the Director of Defense Research and Engineering, DMIC Report 167, Defense Metals Information Center, Battelle Memorial Institute, Columbus, Ohio, March 12, 1962). 499

Abstract

This report summarizes information on refractory composites for use above 2500°F. presented at the Fifth Refractory Composites Working Group Meeting held in Dallas on August 8-10, 1961. The subject of refractory composites is extensive; reports presented at this meeting dealt with protective coatings, heat-resistant ceramic composites, dispersion strengthening, plasma spraying, and high-temperature reactions.

Protective metallic and intermetallic coatings are currently under development for vanadium and the four refractory metals. Most attractive are the silicide coatings, which are protective to temperatures in the vicinity of 3000°F. Recent developments on the silicide coatings include the use of a fluidized-bed technique for application of the coating, optimization of process variables for the pack-cementation application method, and recognition of substrate alloying effects on coating protectiveness. Aluminide coatings are simpler to apply, although generally not protective to as high temperatures as the silicides. The application of silicide and aluminide coatings to actual space-vehicle components has shown that coating uniformity, edge protection, and repairability are serious problems.

Above the temperatures to which coatings are usable, composites utilizing insulating ceramics will be employed. These may consist of zirconia-graphite combinations, refractory metal-reinforced zirconia shells, or metal structures cooled by evaporation of a resin from a porous ceramic facing. These ceramic composites are under study primarily for critical nose-cone applications, where temperatures up to 5000°F. are expected during re-entry of space vehicles.

Refractory composites are also under development for rocket nozzles, which must withstand high-temperature oxidation and/or erosion during firing. Potential improvements over the current tungsten and graphite nozzles include the use of ceramic throat inserts, nozzles coated with silicides, cermets, and pyrolytic materials, as well as the use of transpiration-cooled tungsten nozzles. These materials have shown promise at flame temperatures up to 6300°F.

Progress has also been shown in the direction of metal strengthening by special dispersion techniques. Sapphire whiskers have improved the strengths of aluminum and silver by twofold and fivefold, respectively. The use of whisker reinforcement in refractory materials poses serious problems, however, in view of the rapid reaction and interdiffusion rates which may be expected between the whiskers and matrices at high temperatures.

The high temperature developed in the plasma arc make this a valuable tool for both spraying and evaluation of refractory composites. Studies on the temperature and pressure variations in the arc should prove valuable in the application of the plasma torch. The plasma test facility now under construction will be of importance in the study of space-vehicle components, since plasma conditions exist near the frontal sections of vehicles during re-entry.

Pezdirtz, George F., Erectable Space Structures - Echo Satellites. (NASA Langley Research Center, Langley Station, Hampton, Virginia, for Presentation at the Society of Aerospace Material and Process Engineers Symposium, St. Louis, Missouri, May 7-9, 1962). 500

Abstract

The problems encountered in the design, testing, and production of giant erectable space structures are many and varied. They range from the materials requirements to the need for ultrathin passive thermal control coatings. The research and development programs which were carried out for Echo I provided a firm basis from which to proceed for the followup projects - Echo II and Rebound. The use of sub-mil polymer films and laminates as true structural materials in space requires considerable reorientation of viewpoint from their normal use on earth for packaging purposes.

The concepts and tests behind the mechanical technique for rigidizing Echo II in space will be discussed. A practical solution to the problem of thermal control of thin-shelled space structures and some preliminary indications of the effectiveness will also be discussed.

Pisarenko, G.S., Vibrations of Elastic Systems Taking Account of Energy Dissipation in the Material. (Technical Documentary Report No. WADD TR 60-532, February, 1962. Directorate of Materials and Processes, Aeronautical Systems Division, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, Project No. 7351, Task No. 73521, Prepared under Contract No. AF 33(616)-6828, by the University of Minnesota). 501

Abstract

This monograph is devoted to an analytical and experimental investigation of vibrations of nonconservative elastic systems in which the sources of energy dissipation is irreversible cyclic straining of the material.

Modern methods of analysis of non-linear vibrating systems are extended to treat problems of the flexural vibrations of long bars of constant and variable cross section, short bars and turbine blades. Torsional vibrations of rods are also considered.

Considerable attention is given to the experimental investigation of energy dissipation in the material. Several apparatuses are described and some of the experimental results presented.

Robbins, David L., and Epstein, George, Thermal Erosion of Ablative Materials. (Aerojet-General Corporation, Materials Central, Contract No. AF 33(616)-6285, Project No. 7340, Aeronautical Systems Division, Air Force Systems Command, United States Air Force, Wright-Patterson Air Force Base, Ohio). 502

Abstract

An investigation was conducted to determine the erosion resistance of ablative materials. The materials were examined in the form of rocket nozzle specimens using a gaseous hydrogen-gaseous oxygen rocket motor as the exposure facility. All specimens were supplied by the contracting agency.

Environmental exposure was accomplished at a combustion-chamber pressure of approximately 500 psia and a flame temperature of 5500° F. Measurement was made of the time required for the chamber pressure to decay to 200 psia. This time period depends on the nozzle materials and construction, and is a measure of the thermal-erosion resistance of the specimen. The experimental method provided information on the comparative thermal-erosion-resistant properties of the various research specimens.

A total of 55 nozzles were evaluated; the chamber-pressure decay time varied from 0.9 to 14.9 sec. The majority of the specimens were composed of a continuous -phase resin, usually reinforced with fibers of glass, asbestos, nylon, alumino-silicate glass, high-silica glass, or graphite, and sometimes filled with ceramic or graphite particles.

JOINTS

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Horton, R.E., Joining Methods for Brittle Materials. (Allowables 503
Research Memorandum No. 8, Boeing Airplane Company, 1960).

Abstract

This document reports the results of a program to investigate various problems encountered in joining brittle ceramic materials. Two types of clamped joints were tested, and also several bolted joints. The clamped specimens were fabricated from graphite. The bolted specimens were fabricated from both graphite and alumina. The clamped joints failed at 50 and 65 percent of the control specimens based on gross area strength while the bolted joints failed at 25 to 30 percent of the control specimens based on gross area strength. Although this seems low for the bolted joints, it is much higher than that predicted from theoretical stress concentration factors.

Attempts were made to attain a glass bond of Kovar to alumina which would be useful to 110-1200° F. This work was unsuccessful because bubbles occurring in the ceramic adhesive greatly weakened the bond strength.

Some investigation was made of ceramic fasteners loaded in tension. Three thread types were evaluated photoelastically. A light-bulb type thread gave the best results of those evaluated.

Lobbett, J.W., and Robb, E.A., Thermo-Mechanical Analysis 504
of Structural Joint Study. (Technical Report No. WADD TR 61-151, Project No. 1367, Task No. 14002, Flight Dynamics Laboratory, Aeronautical Systems Division, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, under Contract AF 33(616)-6879, Douglas Aircraft Company, Santa Monica, California, January, 1962).

Abstract

An investigation was conducted to determine new thermo-mechanical analytical methods suitable for high speed airframe bolted and brazed joint design. High-temperature strain gage and photothermoelastic test substantiations, respectively, were made. Realistic envelopes of trajectories were examined; compatible temperature and load data were computed and temperature distributions in the joints were obtained analytically and experimentally.

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Neff, C. W., and Frank, R. G., Refractory Metals Structural Development Program. Volume I: Selection and Analysis of Structural Component. (Technical Report No. ASD-TR-61-392, Vol. I, Prepared under Contract No. AF 33(616)-6578, by McDonnell Aircraft Corporation, General Electric Company, St. Louis, Missouri, Project Nos. 1368 and 7381, Task Nos. 13719 and 73810, ASD-TR-61-392, Volume I, Flight Dynamics Laboratory and Directorate of Materials and Processes, Aeronautical Systems Division, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, June, 1962).

Abstract

The unique requirements of this program has effected close cooperation of interrelated groups involving structural engineers, designers, fabrication specialists, physical and process metallurgists, coating and test specialist. This constitutes a fruitful approach to the complexity of problems at hand and provides a guide as to how such programs should be administered in the future. An immediate result of this type of approach has been the resolution of many problems involving the integration of various technologies and is likely to result in a more realistic and rational approach to over-all problems in the future.

Distinctive problem areas encountered in this program included: (1) material processing, (2) joining, and (3) coating. Many phases of these problems have been partially solved and the sponsoring agency has initiated supplemental programs to investigate and solve other phases of the same problems and also, other problems.

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Ripling, E. J., Mostovoy, S., Novak, G. E., and Patrick, R. L., (Materials Research Laboratory, Inc., Richton Park, Illinois), Application of Fracture Mechanics to Adhesive Joints. (First Status Report, Contract: Nonr - 3544(00)(x) for Department of the Navy, Office of Naval Research, Washington, D.C., NRL Project No. 62-R05-19A, Technical Memo No. 207, June, 1961-March, 1962).

Abstract

The application of fracture mechanics to adhesive joints requires a specimen type and testing procedure in which brittle crack growth is controllable. As an extension of earlier work on homogeneous materials, large plates were edge bonded and tested by use of a loading hole on the center of the glue line. Since crack growth control was not possible in test pieces of

this type, several modifications were made resulting in an edge loaded double beam specimen. Using this shape crack growth could be observed, and G_c determined with a large number of controlled crack arrest points.

Procedures have been developed for preparing these aluminum-epoxy - aluminum test pieces with transparent, bubble-free joints. As expected, thicker joints are springier than thin ones, and G_c values for the former are about twice as high as for the latter.

Evaluation of G_c by the selected test procedure involves measurements of specimen compliance as a function of crack length. Reference measurements made on solid saw-cut aluminum specimens indicate that compliance-crack length curves are similar to those obtained on bonded specimens for joint thickness $\leq .020"$. However, observed compliance curves in solid aluminum, as well as in joints, could not be predicted by even sophisticated modifications of the beam formulae.

Using the "stability factor" form developed by G. Irwin in conjunction with theoretical compliance equations, a set of stability factor-crack length curves was obtained for various specimen configurations. From these curves it appears that adherend geometry is at least as important a factor in brittle failures of adhesives as is the decrease in fracture toughness experienced in thin joints.